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EVALUATION OF ALUMINUM-COATED WIRES AS REINFORCEMENT FOR ARTICULATED CONCRETE MATTRESSES

BASIC PROGRAM

TECHNICAL REPORT NO. 6-613

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U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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PREFACE

The investigation reported herein was authorized by the President, Mississippi River Commission, in the third indorsement, dated 8 March 1960, to a letter dated 30 November 1959, subject, "Evaluation of Proposed Reinforcement for Articulated Concrete Mattress." The investigation was a result of correspondence in October 1959 between the Director, U. S. Army Engineer Waterways Experiment Station, and the President, Mississippi River Commission, followed by a conference held at the Mississippi River Commission on 6 November 1959.

The work was conducted at the Concrete Division, Waterways Experiment Station, by personnel of the Chemistry Section, under the supervision of Messrs. Thomas B. Kennedy, Bryant Mather, and Leonard Pepper. This report was prepared by Mr. Pepper.

Col. Edmund H. Lang, CE, and Col. Alex G. Sutton, Jr., CE, were Directors of the Waterways Experiment Station during the conduct of this work and preparation and publication of this report; Mr. J. B. Tiffany was Technical Director.

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SUMMARY

A laboratory study was conducted to evaluate the possible use of aluminum-clad wires as a corrosion-resistant reinforcement for articulated concrete mattresses as compared to the copper-clad wires that are presently being used. Corrosion resistance of spring steel and stainless steel wires was also determined. Spring steel was included as a control metal, since unprotected carbon steel is known to have a relatively short life when subjected to exposure to Mississippi River water.

Specimens of the various types of wire were tested to determine tensile strength, resistance to bending, quality and thickness of coating, and resistance to abrasion. In addition, corrosion measurements were made on each type of wire after exposure under various conditions for 2, 4, 8, 16, 32, 64, 128, and 256 days. The various exposure conditions were: (a) partial embedment in 2-in. mortar cubes which were then stored in (1) air at 73 F and 100% relative humidity, (2) air at 100 F for 8 hr and then immersed in distilled water for 16 hr, (3) distilled water, and (4) running tap water; and (b) complete, partial, or alternate immersion in salt, pH 5, and alkaline solutions. Different types of wire were coupled together, and tested in the salt and pH 5 solutions to determine the galvanic effect on the corrosion penetration rate. The effect of pinholes in the clad wires when immersed in the salt and pH 5 solutions was also investigated. To evaluate the results of the tests with regard to the degree of corrosion that might be expected in the field, a compilation was made of the available water analyses of the Mississippi River, within the boundaries of the Lower Mississippi Valley Division.

It was found that:

a. The aluminum-clad wires are readily and severely attacked by alkaline media such as are normally found both in concrete and in the Mississippi River, whereas copper-clad and steel wires are not.

b. The resistance of the aluminum-clad wires to corrosion in either salt or slightly acid solutions was much better than that of the spring steel but was not equal to that of the copper-clad or the stainless steel wires.

c. The galvanic effect resulted in an increase in the rate of corrosion of aluminum and a decrease in that of copper. The

galvanic effect on spring steel resulted in an increase in the rate of corrosion of the steel when coupled with copper and a decrease when coupled with aluminum.

d. A 0.021-in.-diameter pinhole in clad wires is large enough to cause a galvanic effect between the coating and the core metal.

e. The aluminum coating of the aluminum-clad wires abrades approximately twice as fast as the copper coating of the copper-clad wires.

It is recommended that aluminum-coated wires not be used as reinforcement for articulated concrete mattresses.

EVALUATION OF ALUMINUM-COATED WIRES AS REINFORCEMENT FOR ARTICULATED CONCRETE MATTRESSES

BASIC PROGRAM

PART I: INTRODUCTION

1. Articulated, reinforced concrete mattresses are used by the Corps of Engineers to stabilize much of the banks of the Mississippi River between New Orleans, La., and Cairo, Ill. The life of the mattress has been found to depend upon the corrosion resistance of the reinforcing fabric. Copper-clad steel wires have been used as the reinforcement for a number of years. The corrosion resistance of copper-clad steel wires was compared with that of other metals, alloys, and combinations of alloys in tests conducted by the U. S. Army Engineer District, Memphis, during the period 29 October 1934 to 6 November 1937. A final report on these tests was published on 31 May 1939.[2*]

2. Two types of copper-clad wires are now being used: "copperweld," produced by an elevated-temperature rolling and wire-drawing process, and "copperply," produced by a double electroplating process. The wire diameter is either 0.182 or 0.202 in. depending upon whether the wire is to be used for reinforcement or as a twist wire to join the articulated sections together. The thickness of the copper coating is at least 0.006 in.

3. The Mississippi River Commission in 1947 considered the possible use of aluminum alloy wires. However, these alloys did not meet the necessary physical requirements, and corrosion studies were not conducted. The Commission was informed, in 1959, of the availability of aluminum-clad steel wires which would meet the physical requirements and, in addition, would cost approximately 35% less than the copper-clad steel wires. The cost of the copper-clad wires is $6.28 per square (100 sq ft of mattress), and the cost of the aluminum-clad wires was estimated to be $4.43 per square. The use of the aluminum-clad wire, if acceptable, would represent a substantial saving since 550,000 to 580,000 squares of articulated concrete mattress are produced each year. Two types of aluminum-clad wire

* Raised numerals refer to similarly numbered items in the List of References at end of text.

were thought to be available: "aluminized" steel wire produced by a process similar to galvanizing; and "alumoweld" produced by a low-temperature rolling and wire-drawing process. The Commission authorized the laboratory study reported herein to evaluate the aluminum-clad wires as a corrosion-resistant reinforcement for articulated concrete mattresses as compared to the copper-clad wires presently being used.

PART II: MATERIALS AND TEST METHODS

Materials

4. Approximately 1200 ft (one coil) of each of the following five different types of wire were obtained for this investigation. Aluminized wire was not available at the time corrosion testing was started and was, therefore, omitted from this investigation.

Symbol	Type of Wire
MRC-2 Al-1	Alumoweld
MRC-2 Cu-1	Copperweld
MRC-2 Cu-2	Copperply
MRC-2 SS-1	18/8 stainless steel, type 302
MRC-2 BS-1 (Control)	Untempered premier spring steel, Sx 3972, Heat Y-7104

Physical Tests

5. Samples, cut from the two ends and the middle of the coil of each of the five types of wire, were tested in tension and for resistance to bending. Samples of the three clad-steel wires (alumoweld, copperweld, and copperply) were also tested for quality and thickness of coating. The methods of test and test requirements are given in Appendix A of this report and were taken from Invitation for Bids No. CIVENG-40-041-59-88, paragraphs TP 2-01a, c, and d, and TP 2-02a, b, c, and d. The ferroxyl test, used to determine the quality of the coating, had to be modified to test the aluminum coating. The modification consisted of cleaning the aluminum-clad wires by immersion in concentrated nitric acid for 2 min rather than by immersion in a 15 or 50% solution of hydrochloric acid for 60 or 3 min, respectively.

Corrosion Studies

Specimen preparation

6. Specimens, 4 in. long, were cut from the two ends and the middle

of each coil of wire. The specimens of each type of wire were mixed after being cut in order to prevent segregation in accordance with coil position. After cleaning, the specimen weight and length were recorded. A numbered gummed tape was affixed to one end of each wire for identification as shown in photograph 1, except that for those specimens that were to be suspended in a solution, a length of nylon monofilament spinning line was tied to the specimen and the gummed identification tape was fastened over the nylon line. Both ends of each specimen were protected by a paraffin wax coating. The wax coating completely covered the identification tape, and, therefore, covered approximately 1/4 in. of the specimen length at one end of the wire, and approximately 1/8 in. at the other end.

Test solutions and
exposure conditions

7. It was planned to test specimens of each type of wire either cast in mortar cubes and exposed to air and to water or exposed directly to the following test solutions: (a) 5000 ppm NaCl (pH 7); (b) dilute H_2SO_4 buffered at pH 5; and (c) a high pH solution made with 0.5 g NaOH plus 0.5 g KOH per 100 ml of distilled water (pH > 12). The latter solution was to simulate the alkaline conditions in fresh concrete. However, testing of specimens by completely and alternately immersing them in this solution (see test condition B in paragraph 8) resulted in a concentrated attack on the alumoweld wire and no effect on the other types of wire; therefore, this solution was not used for the other test conditions. During the exposure tests the solutions and distilled water were kept at 100 F and were changed every 7 days.

8. Specimens of each type of wire were tested under each of the four following conditions. A total of 24 specimens were stored in separate 2-liter plastic containers for each type of wire, exposure condition, and solution. Corrosion measurements were made after exposure for 2, 4, 8, 16, 32, 64, 128, and 256 days.

a. Condition A: Three specimens of each type of wire were cast in 2-in. mortar cubes with from 1 to 1-1/2 in. of each specimen embedded in the mortar. The cubes were exposed as follows:

(1) In air at 73.4 ± 2 F and 100% relative humidity

(2) Alternately in air at 100 F for 8 hr and then immersed in distilled water for 16 hr

(3) In distilled water

(4) In running tap water

b. Condition B: Specimens of each type of wire were:

(1) Completely immersed in the test solutions

(2) Partially immersed; that is, suspended vertically with 2-1/2 to 3 in. of the specimen immersed in the test solutions

(3) Alternately completely immersed in the test solutions for 1 hr and then dried in 100 F air for 1 hr

c. Condition C: The galvanic effect on the corrosion rate was determined by tying with nylon thread the alumoweld wire to each of the two copper-clad wires, the alumoweld wire to the spring steel wire, and each of the two copper-clad wires to the spring steel wire. The five different couples, in separate plastic containers, were completely, partially, and alternately immersed (conditions B(1), (2), and (3)) in both the NaCl and pH 5 solutions.

d. Condition D: The effect of a pinhole on the corrosion rates was determined by drilling a hole of known diameter in the specimens and partially and alternately (conditions B(2) and (3)) immersing the specimens in the NaCl and pH 5 solutions. The pinhole effect was not determined for the stainless steel wires. Each specimen of the three types of clad wires was examined to ascertain that the coating was free of defects before the pinhole was drilled. It was originally planned to determine the effects of holes 0.003, 0.009, and 0.021 in. in diameter. However, the results obtained by testing specimens with a pinhole having a diameter of 0.021 in. were sufficiently conclusive and it was not necessary to determine the effects of 0.003- and 0.009-in. pinholes.

Method of determining degree of corrosion

9. The degree of corrosion was determined by visual observations and by the change in weight of the specimens. Before the corroded specimens were weighed, the wires were first carefully wire-brushed and then chemically cleaned. The following cleaning solutions were used:

Metal	Solution	Immersion Time, min
Copper	5% nitric and 2-1/2% oxalic acids	5
Steel	1:10 sulfuric acid	2
Aluminum	Concentrated nitric acid	2

At the later ages it was often necessary to lightly rub the specimens after chemical cleaning with very fine steel wool to remove all the corrosion. The corroded spring steel wires required rubbing with fine emery cloth followed by steel wool. All the specimens after cleaning were weighed to the nearest 0.1 mg. Specimens that had been exposed to the effects of a corrosive medium for a specified time and then removed, cleaned, and weighed were not reexposed for additional periods of time. Data on effects of longer exposure were obtained by use of additional specimens continuously exposed for specified times.

Abrasion Studies

10. T effect of abrasion on the clad wires was determined by suspending specimens, prepared as described in paragraph 6, in agitated slurries prepared with varying concentrations of either fly ash or natural siliceous sand. Weight losses of the specimens were determined after 1, 3, and 7 days of abrasion.

Analyses of Mississippi River Water

11. To evaluate the results of this investigation with regard to the degree of corrosion that might be expected in the field, a compilation was made of the available water analyses of the Mississippi River within the boundaries of the Lower Mississippi Valley Division.

PART III: TESTS AND RESULTS

Physical Tests

Tensile strength

12. Tensile strength test results are shown in table 1. All the wires were found to meet the test requirement of having a breaking strength of not less than 4000 lb.

Resistance to bending

13. The results of the bending tests are shown in table 2. All the wires except spring steel were found to meet the test requirement of withstanding a minimum of seven 90-degree bends without breaking. Six of the nine spring steel specimens, those taken from the center and lower end of the coil, failed to meet the minimum bending requirement. The other three spring steel specimens, those taken from the upper end of the coil, did just meet the minimum requirement. The coatings of the three types of clad wires did not separate from the core during the bending test. In addition, specimens of the three types of clad wires were found capable of being wrapped around their own diameter for eight consecutive turns with a pitch substantially equal to the diameter of the wire without visible signs of coating breaks.

Quality of coating

14. Specimens of the three types of clad wires wrapped eight times around their own diameter with a pitch substantially equal to the wire diameter were tested for quality of coating by means of the ferroxyl test. Six specimens taken from the center and the lower end of the copperply coil were found to have coating imperfections. The other three copperply specimens, taken from the upper end of the coil, and all the copperweld and alumoweld specimens were free of coating imperfections.

Coating thickness

15. The coating thickness of the clad wires was determined by first grinding the ends of the specimens, then etching the exposed cross section and finally examining the treated section under a microscope fitted with a calibrated micrometer eyepiece. The coating thicknesses were as follows:

Wire	Coating Thickness in.	cm
Copperply	0.008	0.0200
Copperweld	0.013	0.0323
Alumoweld	0.012	0.0313

The three clad wires met the minimum coating thickness requirement of 0.006 in.

Corrosion Studies

Expression of results

16. The degree of corrosion of the specimens was determined as a weight loss in milligrams per 10-cm length of specimen. Quantitative corrosion rates are normally reported[1] as either a weight loss per unit area per day or as corrosion penetration per year. The latter expression is more meaningful for comparing corrosion rates of dissimilar metals. Both expressions are subject to error because of nonuniform distribution of corrosion over the specimens. The degree of corrosion is shown in this report as an average corrosion penetration (average of three specimens) in 10^{-4} cm, along with a general description of the corrosion of the specimens. The corrosion penetration was calculated from the weight loss data by assuming the densities of the four different metals to be:

Metal	Density, g/cc
Spring steel	7.75
Stainless steel	7.81
Copper	8.92
Aluminum	2.72

The first two densities were determined directly from the wire furnished for this investigation. The last two densities were taken from suggested values in ASTM Test Method B 185-43T.[1]

Specimens embedded in mortar cubes

17. The corrosion penetration results for this series of tests are summarized in table 3. The effects on the five different types of wire after 32 days of exposure to the three different storage conditions

(conditions A(1), (2), and (3), paragraph 8) can be seen in photographs 1, 2, and 3, which were taken just after the specimens were removed from the mortar cubes. At all test ages, the corrosion of the two steel wires and the two copper-clad wires was confined to the nonembedded portions of the specimens; the mortar protected the embedded portions of these specimens from corrosion. The corrosion of the nonembedded portions of the stainless steel and the two copper-clad specimens was slight and uniform and also apparently independent of the length of the exposure up to the test age of 256 days. The nonembedded portion of the spring steel wire was markedly pitted, and the severity of the pitting increased with time. Three rates of corrosion penetration of spring steel wire are shown in plate 1. The most severe rate (56×10^{-4} cm per yr)* was induced when the specimens were stored immersed in distilled water. The least severe rate (20×10^{-4} cm per yr) was found for those specimens that were exposed to air at 73 F and 100% relative humidity. The rate shown for both storage under running tap water and storage under alternate wet and dry conditions (29×10^{-4} cm per yr) is between the two extremes. However, this rate would be the same as that for storage immersed in distilled water except for the data obtained at the last test age of 256 days.

18. The corrosion of the alumoweld specimens differed from that described above for the other four types of wire. The embedded portion of the alumoweld specimens reacted rather severely and nonuniformly with the mortar. Pitting was particularly severe on that part of the specimen that was in contact with the upper face of the mortar cube, and in a few specimens the core metal was exposed. The reaction of the aluminum coating with the alkalies of the mortar was not dependent upon the length of exposure (see photographs 4, 5, and 6), but seemed to vary with the particular batch of mortar used in casting the cubes. The nonembedded portion of the alumoweld wire was not affected by exposure to air at 73 F and 100% relative humidity. However, storage immersed in distilled water, or alternately wetted and dried, resulted in etching of the aluminum coating. The degree of corrosion increased with storage time, and severe pitting, exposing the core metal, was found after 128 days storage. The pH of the distilled

* The curves in plates 1-14 were extrapolated to 365 days to determine the corrosion penetration rate per year.

water in which the cubes were stored was found to rise rapidly from 6.5 to a value greater than 10. Duplicate specimens were cast and stored under running tap water. Again, because of the presence of the mortar cubes, the pH rose from 7.8 to approximately 9, and similar corrosion penetration results were obtained. Corrosion rates were not calculated for the alumoweld specimens since the aluminum coating was attacked by two corrosive media, mortar and alkaline water.

Specimens stored in alkali solution

19. Little, if any, corrosion penetration resulted from exposure of the two steel and the two copper-clad wires to the alkali (high pH) solution. However, the aluminum coating was completely stripped from the alumoweld wire after 2 or, at the most, 4 days immersion in the alkali solution.

Specimens stored in salt
and in slightly acid solutions

20. The corrosion penetration results obtained by storing the wire specimens in the salt and in the slightly acid solutions are summarized in tables 4 and 5. The corrosion rates for each type of wire, except stainless steel, are shown in plates 2-5. The following observations may be made concerning the corrosion of the five types of wire in 5000 ppm NaCl and in pH 5 solutions.

21. Stainless steel. Visual observations of the specimens indicated very little corrosion. Those stainless steel specimens that were partially immersed in the salt solution showed slight pitting above the solution level at 128 days. Slight pitting uniformly distributed over the length of the specimen was also observed at 128 days for those specimens that were alternately immersed in the salt solution and dried. The data in tables 4 and 5 indicate that the corrosion rates were very low. Therefore, curves were not drawn for these specimens.

22. Spring steel. The corrosion product formed as a result of exposing the spring steel (control) wires to salt solution was different from that formed from exposure to slightly acid solution. Exposure of the spring steel specimens to the pH 5 solution caused pitting and a relatively hard corrosion product which adhered tightly to the uncorroded metal. Increased storage time appeared to increase the number of pits formed.

Exposure to the salt solution also caused pitting; however, the corrosion product was relatively soft and adhered rather loosely to the uncorroded metal. Increased storage time increased the number of pits and also increased the area covered by the first pits formed. The corrosion product produced by the salt water appeared to flake off the specimen. Partial immersion of the wire in both corrosive solutions produced pitting on the submerged portion of the specimen. However, the pits appeared deeper and wider at the interface of the acid solution and air. Immersion in salt water produced, in general, a greater rate of corrosion penetration than immersion in slightly acid water. In addition, the rate of corrosion penetration was greatest for alternate immersion and drying and least for complete immersion. Only one rate curve is shown in plate 2 for complete immersion as there was little difference in the data for the two solutions. The following rates are estimated from the curves shown in plate 2:

Storage Condition	Rate of Average Corrosion Penetration of Spring Steel Wire in 10^{-4} cm/yr	
	NaCl Solution	pH 5 Solution
Alternate immersion	1048	338
Partial immersion	262	206
Complete immersion	97	97

23. Copper-clad wires. No difference could be observed between the corrosion products resulting from immersion of the copper-clad wires in either the salt or pH 5 solution. Partial immersion of the copper-clad wires in both the salt and acid solutions produced a more concentrated corrosion on the portion of the specimen above the solution. Complete or alternate immersion in either solution produced a uniform corrosion over the entire length of the specimen. For both copper-clad wires, immersion in salt water produced, in general, a greater rate of corrosion penetration than immersion in pH 5 solution. Also, for both copper-clad wires, the rate of corrosion penetration was greatest for partial immersion and least for alternate immersion. Since the data for complete immersion for both copper-clad wires were somewhat erratic, only one rate curve is shown for this storage condition in both solutions in plates 3 and 4. In addition, only one rate curve is shown in plate 4 for alternate immersion of copperweld wire since there is little difference in the data for the

two solutions. The following rates are estimated from the curves shown in plates 3 and 4:

Storage Condition	Rate of Average Corrosion Penetration of Copper-Clad Wires in 10^{-4} cm/yr			
	Copperply		Copperweld	
	NaCl Solution	pH 5 Solution	NaCl Solution	pH 5 Solution
Partial immersion	112	97	154	81
Complete immersion	54	54	50	50
Alternate immersion	25	10	15	15

24. Alumoweld. The data for alumoweld in tables 4 and 5 seem to indicate that corrosion penetration was less, with a few exceptions, than that for the two copper-clad wires. Visual examination indicated, however, that the alumoweld corrosion was generally in the form of a few pits scattered over the specimen, or along flaw lines in the coating of the specimen. Increased storage time generally increased the area and depth of the pits rather than increasing the number of pits. At 128 days storage the pits had become deep enough to expose the core metal. Partial immersion of alumoweld specimens in either solution caused corrosion in that portion of the specimen above the liquid. The data plotted in plate 5 are somewhat erratic, and only one rate curve was drawn to approximate all the data. The rate of average corrosion penetration is estimated to be 17×10^{-4} cm per yr.

Galvanic effects

25. The galvanic effect was determined as the corrosion penetration in a specimen which occurs as a result of tying two dissimilar specimens together. Galvanic effects on alumoweld, copperply, copperweld, and spring steel are summarized in tables 6-9. To show the change in corrosion penetration due to the galvanic effect, the corrosion penetration data in the applicable parts of tables 4 and 5 are also shown in tables 6-9 as the "normal penetration." The rates of corrosion penetration due to galvanic effect of alumoweld and spring steel wires are shown in plates 6-10. To show the change in the rate of corrosion penetration due to the galvanic effect, the applicable rate curves in plates 2 and 5 are also shown in plates 6-10 as the "normal rate." The following observations may be made concerning the galvanic effect

on corrosion of each of the four types of wires tested.

26. Alumoweld. Visual examinations of the corroded specimens indicated that alumoweld corrosion was generally more severe than is evident from the quantitative corrosion penetration data, particularly at early ages. Partial immersion of couples, of which one member was alumoweld, in either solution resulted in corrosion of that portion of the alumoweld specimen that was above the solution level. At later ages the alumoweld specimens also corroded below the solution level. Both complete and alternate immersion in either solution resulted in pits scattered over the entire length of the alumoweld specimen and frequently along what appeared to be flaw lines in the aluminum coating. The test age at which the pits became deep enough to uncover the core metal depended upon the solution in which the couples were immersed, the storage condition, and also the metal with which the alumoweld was coupled. The core metal was found to be exposed at the following ages:

	Storage Time at Which Alumoweld Core Metal Was Exposed, days			
	pH 5 Solution		NaCl Solution	
Storage Condition	Coupled with Copper-Clad Wire	Coupled with Spring Steel Wire	Coupled with Copper-Clad Wire	Coupled with Spring Steel Wire
Partial immersion	64	128	16	32
Alternate immersion	256	256	16	16
Complete immersion	128	256	128	128

The corrosion in the salt solution was particularly severe. The following estimates were made of the amount of core metal exposed at 256 days as a percentage of the total surface area of the alumoweld specimen:

	Area of the Exposed Alumoweld Core Metal, %	
Storage Condition	Coupled with Copper-Clad Wire	Coupled with Spring Steel Wire
Partial immersion	10-50	10-30
Alternate immersion	25-100	25-100
Complete immersion	Up to 10	Up to 10

27. The galvanic effect on alumoweld rate of corrosion penetration is shown in plates 6 and 7. The data are rather variable, possibly due to

the concurrent corrosion of the alumoweld core metal. The particular effect of each of the dissimilar metals could not be detected except for the case of the partial immersion of the couple in the pH 5 solution. The galvanic effect resulted in an increase of the alumoweld rate of corrosion penetration for all conditions except alternate immersion of the couple in pH 5 solution, and the rate for this storage condition is approximately equal to the normal rate of 17×10^{-4} cm per yr. The following rates were estimated from the curves drawn in plates 6 and 7:

Storage Condition	Average Galvanic Corrosion Rate of Alumoweld Wire in 10^{-4} cm/yr	
	NaCl Solution	pH 5 Solution
Alternate immersion	380*	17
Partial immersion, coupled with copper-clad wires	128	63
Partial immersion, coupled with spring steel	128	26
Complete immersion	67	50

* The value of 380×10^{-4} cm per yr exceeds the aluminum coating thickness which is 313×10^{-4} cm.

28. Copper-clad wires. The corrosion produced on the copper-clad specimens when coupled with either alumoweld or spring steel was uniform over the entire length of the specimen, except for the storage condition in which the couple was partially immersed in either corrosive solution. When the couples were partially immersed in either solution, the corrosion of the copper-clad wires was concentrated on that part of the specimen above the solution level. The data in tables 7 and 8 indicate that the galvanic effect caused a reduction in the corrosion penetration rate of the copper-clad wires as compared to the normal rate for those conditions in which the specimens were either partially or completely immersed in either solution. A greater reduction from the normal rate was obtained when the copper-clad wires were coupled with the spring steel than when they were coupled with the alumoweld wires. Neither the spring steel nor the alumoweld wires significantly changed the corrosion rate of the copper-clad wires when the couples were alternately immersed in either solution.

29. Spring steel. The corrosion produced on the spring steel

specimens when coupled with either alumoweld or copper-clad wires was uniform over the entire length of the specimen, except for the storage condition in which the couple was partially immersed in either corrosive solution. When the couples were partially immersed in either solution, the corrosion of the spring steel wires was concentrated on that part of the wire immersed in the solution. The galvanic effect on the corrosion rates of spring steel is shown in plates 8-10. Alternate immersion in NaCl is shown separately in plate 8 because of the unexplained reduction in the spring steel corrosion penetration at 256 days. The results at 256 days may be in error, and the estimated rates of corrosion penetration of spring steel shown below for this storage condition are based on the 64- and 128-day data. The change in slope of the curve shown in plate 8 for the spring steel-alumoweld couple at 64 days may have been due to the exposed core metal on the alumoweld specimen. In general, the galvanic effect of copper on the rate of corrosion penetration of spring steel is either zero or positive. The galvanic effect of aluminum on the rate of corrosion penetration of spring steel is either zero or negative except for the case of alternate immersion in pH 5 solution. The following corrosion rates were estimated from the curves shown in plates 8-10:

	Spring Steel Corrosion Penetration Rate, 10^{-4} cm/yr		
Storage Condition	Coupled with Copper-Clad Wire	Normal Rate	Coupled with Alumoweld Wire
Alternate immersion in NaCl solution	1085	1048	900
Partial immersion in NaCl solution	322	262	172
Complete immersion in NaCl solution	115	97	55
Alternate immersion in pH 5 solution	376	338	376
Partial immersion in pH 5 solution	206	206	133
Complete immersion in pH 5 solution	97	97	97

Effect of pinholes

30. Specimens of the three types of clad wires were examined to ensure that they were completely free of surface coating imperfections before the pinholes were drilled. Each hole was drilled deep enough to ensure exposure of the core metal. Testing of the specimens was the same as

in the other corrosion studies except that complete immersion in NaCl and pH 5 solutions was omitted. The corrosion penetration data are shown in tables 10 and 11 along with the normal corrosion data for each storage condition. The normal corrosion data were taken from the applicable parts of tables 4 and 5. The effects of pinholes on corrosion rates are shown in plates 11-14. The normal rates that are also shown in plates 11-14 were taken from plates 2-5. The following observations may be made concerning the effect of a 0.021-in. pinhole on the corrosion of clad specimens.

31. Spring steel. The physical appearance of the spring steel specimens after storage in both corrosive solutions was the same as described in paragraph 22. The pinholes were not expected to have any effect on the corrosion of spring steel; therefore, this series of tests was expected to be a replicate of the tests described earlier for spring steel. The data for spring steel in tables 10 and 11 and also in plate 11 indicate that the reproducibility of the test was not very good. The normal rates of corrosion penetration for alternate immersion in both solutions may be considered to approximately fit the data in plate 11. However, the normal rates for partial immersion in both solutions are higher than the data in plate 11. One rate curve may be drawn to fit the partial immersion data for both solutions, and it results in an estimated corrosion rate of 158 x 10^{-4} cm per yr. In contrast, the normal rate curves shown in plate 11 for partial immersion in NaCl and pH 5 solutions result in estimated corrosion rates of 262 and 206 x 10^{-4} cm per yr, respectively.

32. Copper-clad wires. After 2 days storage in either solution, all the copper-clad specimens were observed to have iron rust exuding from the pinhole. The exudation appeared to increase slightly at 4 days and cease at 8 days. Copper corrosion was not observed at any time up to and including 256 days in an area around the pinhole having a diameter at least twice that of the pinhole. The 0.021-in. pinhole in the copper-clad specimens may, therefore, be considered to be large enough to create a galvanic effect between the copper coating and the steel core. The data in tables 10 and 11 and also in plates 12 and 13 support this conclusion. The corrosion rate was reduced from the normal rate for those specimens that were partially immersed in either solution. The corrosion rate was found to be the

same as the normal rate for those specimens that were alternately immersed in either solution.

33. Alumoweld wires. An exudation of iron rust was also observed at the pinhole drilled into the alumoweld specimen after 2 days storage in either solution. However, the exudation did not continue after the second day of storage. In addition, the aluminum coating on approximately one-third of the specimens was observed to be corroded close to or on the periphery of the pinhole. A pinhole having a diameter of 0.021 in. is, therefore, large enough to create a galvanic effect, and the aluminum coating is attacked in preference to the core metal. The data in tables 10 and 11 and also in plate 14 support this conclusion. The corrosion rate was increased from the normal rate for those specimens that were partially immersed in either solution or alternately immersed in the NaCl solution. The rate was the same or somewhat below the normal rate for those specimens that were alternately immersed in pH 5 solution.

Effect of Abrasion

Test procedure

34. Specimens of the three clad wires, similar to the specimens used in the corrosion studies, were suspended in slurries made with either fly ash or natural siliceous sand. The slurries and specimens were stored in a large desiccator and agitated with a laboratory stirrer rated at 1600 rpm. Three specimens of each type of wire were removed from the slurry after 1, 3, and 7 days of abrasion, washed with tap water, dried with a soft cloth, and weighed to the nearest 0.1 mg. The effect of abrasion was calculated as a coating loss using the densities shown in paragraph 16.

Effect of fly ash

35. The copper-clad wires were abraded relatively rapidly by the slurry containing fly ash, and the coating was polished to a high luster. The alumoweld wires were found to have gained weight after 1 day of abrasion, and these wires were coated with a dull, hard film. The pH of the slurry was found to be 9, which is high enough to result in attack and corrosion of the aluminum coating. The use of a fly ash slurry to abrade the specimens was, therefore, discontinued.

Effect of natural siliceous sand

36. Two slurries were made with a natural siliceous sand; the first containing sand passing the No. 50 and retained on the No. 100 sieve, and the second containing sand passing the No. 100 sieve. The amount of sand used was sufficient to ensure that the maximum amount of sand would be held in suspension. The coating loss data obtained with these slurries are shown in table 12, and the rates of coating loss are shown in plate 15. The finer sieve fraction of siliceous sand, because of the greater number of particles held in suspension, produced the greater coating loss. Alumoweld wire lost more coating than the copper-clad wires. All the rate curves in plate 15 indicate a coating loss at zero time. This loss is probably the amount of material removed by rubbing the specimens with a soft cloth. Considering the magnitude of this loss at zero time, only one intercept may be taken for each type of wire. These intercepts are 0.20×10^{-4} and 0.04×10^{-4} cm for alumoweld and the copper-clad wires, respectively. The following rates of coating loss due to abrasion were estimated from the curves in plate 15:

Sand Sieve Fraction	Rate of Coating Loss in 10^{-4} cm/yr Alumoweld Wire	Rate of Coating Loss in 10^{-4} cm/yr Copper-Clad Wire
Passing No. 100	60	36
Passing No. 50, retained on No. 100	42	10

Summary of the Water Analyses of the Mississippi River

37. The available data on the constituents of Mississippi River water at various points between New Orleans, La., and St. Louis, Mo., are summarized in table 13. The data were obtained from the National Water Quality Network,[3,4,5] an annual compilation of water data published by the Public Health Service of the U. S. Department of Health, Education and Welfare, and also from communications with Messrs. Schroeder and Kapustka of the U. S. Geological Survey at Fayetteville, Ark., and Baton Rouge, La., respectively. All the samples listed in table 13 were taken and analyzed between 1957 and 1960, except for three samples taken at the MacArthur Bridge at St. Louis which were analyzed in 1952. The data indicate that

the Mississippi River between New Orleans and St. Louis is slightly alkaline. In general, the analyses of the water indicate that the constituents vary with the time and place of sampling.

PART IV: CONCLUSION

Testing Error

38. The expected error of the tests made in this investigation is of the order of 8 to 10%,[1] and for most of the tests the error was of this magnitude. However, at later test specimen ages, in a number of instances, the error was found to be much greater. The increased error is thought to be due to two causes.

- a. Cleaning. A negative error may be expected in testing spring steel due to incomplete removal of the corrosion products, particularly when the specimen is deeply pitted. A positive error may be expected in testing the clad wires due to the ease with which the softer coating may be removed with steel wool.
- b. End coating. Insufficient protection was afforded the ends of the specimens since paraffin wax proved to be a poor cover in these tests. A number of specimens at later ages were found to be completely devoid of any end protection. The expected error is positive and is of particular concern in testing the clad wires because of the galvanic effect between the coating and the core.

Data Analysis

39. The tests conducted in this investigation were designed to provide data that can be easily subjected to statistical analysis, even with the errors discussed above. However, the results of such an analysis on the alumoweld corrosion penetration data may not have any real meaning because of the nonuniform distribution of corrosion over the alumoweld specimens. The test results and observations clearly demonstrate, without statistical analysis, the differences between alumoweld and the copper-clad wires in their response to corrosive media. It should be noted that the test ages were chosen in order that a curvilinear relation between corrosion penetration and time could be easily detected. The results obtained indicate that the relation between the two factors is essentially linear. The curves shown in all the plates of this report were drawn to best fit the data, but were not calculated by the least squares method. The rates of corrosion penetration given herein

may be changed if the least square lines are drawn.

Summary of Results and Conclusions

40. The following conclusions are evident from the results obtained:

a. Alumoweld. The alumoweld wires meet the physical requirements for a reinforcing fabric. However, the aluminum coating is readily etched when the wire is embedded in concrete. The degree of etching is dependent upon the type of concrete, and will vary from batch to batch. The corrosion of alumoweld in concrete is due to the reaction of the aluminum coating with alkaline solutions, and the reaction will start when the solution has a pH of approximately 9 or lower. The rate of this reaction increases with increasing alkalinity. Impurities and imperfections in the aluminum coating will cause pits to form when the alumoweld wire is exposed to either slightly acid or to salt solutions. Because of the nonuniform distribution of the pits, the alumoweld rate of corrosion penetration has little physical meaning. The pits were found to widen and deepen with time, and at 128 days the core metal was exposed. The exposure of the core metal will create a galvanic couple between the aluminum coating and the steel core if the exposed area has an equivalent diameter of approximately 0.021 in. The galvanic effect results in an increase in the rate of corrosion of the aluminum coating. The aluminum coating of the alumoweld wire abrades approximately twice as fast as the copper coating of the copper-clad wires.

b. Copper-clad wires. Both copperweld and copperply meet the physical requirements for a reinforcing fabric except for failure of the copperply specimens to meet the requirements of the ferroxyl test. The copper coating on the copperweld wires was 1-1/2 times as thick as that on the copperply wires even though the overall diameter of the copperply was greater than that of the copperweld. The rates of corrosion penetration of both copper-clad wires were essentially similar in all the tests conducted in this investigation. The rate was highest in the salt solution and practically zero in mortar or alkaline solution. The corrosion was generally uniformly distributed over the specimen and never in the form of pits. The galvanic effect on the copper-clad wires generally causes a reduction in the rate of corrosion rather than an increase as was found for the aluminum-coated wires. A pinhole having a diameter of approximately 0.021 in. is large enough to create a galvanic effect and thereby reduce the corrosion rate. Abrasion of the copper coating was found to be one-half that of the aluminum coating.

c. Spring steel. Spring steel was included as a control metal,

since unprotected carbon steel is known to have a relatively short life when subjected to exposure to Mississippi River water. The spring steel specimens failed to meet the requirements of the resistance to bending test, but did meet all the other physical requirements for a reinforcing fabric. The corrosion products formed in salt and slightly acid solutions were different, and the rate of corrosion penetration was much greater in the salt solution. Corrosion was relatively slight in mortar or in alkaline solutions, but was greater than that of the copper-clad wires and much less than that of the alumoweld wires in these solutions. Spring steel corrosion in salt or slightly acid solutions was much greater than that of the three clad wires. In general, the galvanic effect of copper on the rate of corrosion of spring steel was either zero or positive and the effect of aluminum was zero or negative.

d. Stainless steel. The stainless steel wires met all the physical requirements for a reinforcing fabric. Corrosion tests on the stainless steel wire were limited, but were sufficient to indicate that the corrosion resistance was very high. Slight pitting was evident after 128 days exposure to salt solution and little, if any, corrosion resulted from the other corrosive media.

e. Water analysis of the Mississippi River. The pH of the river water has been found to vary, on the average, from 7.1 to 8.0 and has attained a maximum of 8.8. The results of chemical analysis vary with the time and place of sampling of the water. The river water, because of its pH, would increase the corrosion rate of the alumoweld specimens and have very little, if any, effect on the other types of wire.

Recommendation

41. Alumoweld wires have been found to be readily and severely attacked by alkaline media such as normally found both in concrete and in the Mississippi River. The resistance to corrosion of the aluminum coating is not equal to that of the copper coating in either slightly acid or salt solutions. Therefore, it is recommended that alumoweld wires not be used as reinforcement for articulated concrete mattresses.

LIST OF REFERENCES

1. American Society for Testing Materials, "Materials test methods" (except "Chemical analysis"). 1958 Book of ASTM Standards, Part 3 (Philadelphia, Pa., 1958).
2. U. S. Army Engineer District, Memphis, CE, Report on Corrosion Test of Metals in the Mississippi River. May 1939.
3. U. S. Department of Health, Education and Welfare, Public Health Service, National Water Quality Network. Cincinnati, Ohio, 1 Oct 1957-30 Sept 1958.
4. ________, National Water Quality Network. Cincinnati, Ohio, 1 Oct 1958-30 Sept 1959.
5. ________, National Water Quality Network. Cincinnati, Ohio, 1 Oct 1959-30 Sept 1960.

Table 1

Tensile Strength Results

Wire	Original Position of Sample on Coil	Wire Diameter in.	Breaking Strength lb	Tensile Strength psi
Spring steel	Upper end	0.192	4825	166,400
	Center	0.193	4550	155,300
	Lower end	0.193	4425	151,000
Stainless steel	Upper end	0.215	5065	139,500
	Center	0.216	4890	133,600
	Lower end	0.216	5020	137,200
Copperply	Upper end	0.202	5725	176,700
	Center	0.202	5740	179,400
	Lower end	0.203	5845	180,400
Copperweld	Upper end	0.181	4585	176,300
	Center	0.182	4600	176,900
	Lower end	0.182	4580	176,200
Alumoweld	Upper end	0.182	4545	174,800
	Center	0.182	4515	173,700
	Lower end	0.182	4505	173,300

Table 2

Results of Bending Tests

Wire	Number of 90-degree Bends Before Failure of Samples from Upper End of Coil	Center of Coil	Lower End of Coil
Spring steel	7	4	5
	7	5	3
	7	5	5
Stainless steel	11	11	10
	11	12	11
	13	10	11
Copperply*	12	11	12
	11	11	11
	11	12	11
Copperweld*	12	12	11
	12	13	13
	12	13	11
Alumoweld*	9	8	9
	8	8	8
	9	8	8

* No observed separation of coating.

Table 3

Average Corrosion Penetration, Wires Cast in Mortar, in 10^{-4} cm

Wire	Time, days							
	2	4	8	16	32	64	128	256
Stored in Air at 73 F and 100% Relative Humidity								
Spring steel	4	3	6	7*	8	6	11	16
Stainless steel	4	4	3	4	2	1	2	3
Copperply	1	1	1	1	1	1	1	2
Copperweld	1	1*	1	1	1	1	1	1
Alumoweld	8**	7**	9**	11	8	8	9	10
Alternately in Air and Underwater								
Spring steel	3	2	4	5	10	16	18	20
Stainless steel	2	4	3	2	2	4	4	3
Copperply	1	1	1	1	1	3	1	2
Copperweld	2	1	1	1	2	3	2	2
Alumoweld	12**	12**	14**	16	15	21	12	17
Stored Immersed in Distilled Water								
Spring steel	3	3	2	5	6	10	22	40
Stainless steel	3	4	3	3	2	2	4	3
Copperply	1	1	1	1	1	1	1	2
Copperweld	1	1	1	1	1	1	1	2
Alumoweld	16**	20**	24**	42	38	31	36	34
Stored Under Running Tap Water								
Spring steel	1	1	4	5	8	12	18	24
Stainless steel	1	1	2	1	1	2	1	1
Copperply	1	0	1	1	1	1	2	3
Copperweld	0	1	1	1	1	1	2	3
Alumoweld	7	9	7	9	8	17	27	48

* Average of 2 specimens.
** Average of 6 specimens.

Table 4

Average Corrosion Penetration of Specimens Stored in 5000 ppm NaCl Solution, in 10^{-4} cm

Wire	Time, days							
	2	4	8	16	32	64	128	256
Complete Immersion								
Spring steel	1	2	2	2	6	10	25	70
Stainless steel	2	2	2	2	3	4	3	4
Copperply	0	0	0	1	2	6	15	38
Copperweld	0	0	1	1	2	5	13	42
Alumoweld	1	1	1	3	6	4	4	11
Partial Immersion								
Spring steel	2	2	7*	8	20	40	93	--
Stainless steel	2	1	3*	3	3	3	5	--
Copperply	1	1	3*	3	12	22	42	--
Copperweld	1	1	2*	6	13	24	54	--
Alumoweld	2	3	7*	3	5	5	9	--
Alternate Immersion and Drying								
Spring steel	3	6	8	25	54	173	331	752
Stainless steel	1	1	1	2	2	3	4	3
Copperply	0	1	1	1	3	6	8	18
Copperweld	0	0	0	1	2	5	8	12
Alumoweld	0	0	1	1	4	7	10	16

* Average of 6 specimens.

Table 5

Average Corrosion Penetration of Specimens Stored in pH 5 Solution, in 10^{-4} cm

Wire	Time, days 2	4	8	16	32	64	128	256
				Complete Immersion				
Spring steel	2	2	3	--	14	13	32	77*
Stainless steel	2	2	2	--	4	2	3	3*
Copperply	0	1	1	--	8	8	13	45*
Copperweld	1	1	1	--	8	7	19	43*
Alumoweld	3	3	3	--	9	4	10	15*
				Partial Immersion				
Spring steel	2	2	7*	7	15	32	72	--
Stainless steel	2	2	3*	2	3	2	2	--
Copperply	1	1	1*	3	8	15	33	--
Copperweld	1	1	1*	3	7	13	28	--
Alumoweld	4	3	3*	4	3	4	7	--
				Alternate Immersion and Drying				
Spring steel	2	4	11	--	55	54**	130	220†
Stainless steel	1	1	2	--	3	2**	2	2†
Copperply	1	1	1	--	2	2**	4	7†
Copperweld	1	1	1	--	2	2**	3	8†
Alumoweld	3	2	2	--	5	2**	8	7†

* Average of 6 specimens.
** Average of 4 specimens.
† Average of 5 specimens.

Table 6

Average Galvanic Effect on Corrosion Rate of Alumoweld of Storage in NaCl and pH 5 Solutions for 2 to 256 Days

Coupled with	Average Corrosion Penetration in 10^{-4} cm, When Stored in 5000 ppm NaCl, days								pH 5, days							
	2	4	8	16	32	64	128	256	2	4	8	16	32	64	128	256
Complete Immersion																
Copperply	4	7	6	7	10	20	18	34	1	1	2	4	6	12	16	47
Copperweld	4	5	5	6	13	20	43	38	1	1	1	4	6	10	19	34
Spring steel	5	5	5	6	8	14	24	42	1	1	2	2	3	7	6	33
Normal penetration	1	1	1	3	6	4	4	11	3	3	3	-	9	4	10	15*
Partial Immersion																
Copperply	6	4	11	16	53	56	56	93	1	2	3	5	10	16	26	27
Copperweld	5	7	8	13	23	57	43	92	1	2	4	5	10	12	21	81
Spring steel	3	5	5	11	13	19	50	71	1	1	2	3	5	7	11	19
Normal penetration	2	3	7*	3	5	5	9	--	4	3	3*	4	3	4	7	--
Alternate Immersion and Drying																
Copperply	3	6	12	20	34	78	137	171	1	2	2	3	4	4	7	18
Copperweld	3	7	16	26	65	129	105	313**	2	2	3	3	4	4	7	26
Spring steel	1	2	15	41	38	62	142	313**	2	2	2	3	4	3	5	12
Normal penetration	0	0	1	1	4	7	10	16	3	2	2	-	5	2†	8	7††

* Average of 6 specimens.
** Complete loss of alumoweld coating.
† Average of 4 specimens.
†† Average of 5 specimens.

Table 7

Average Galvanic Effect on Corrosion Rate of Copperply of Storage in NaCl and pH 5 Solutions for 2 to 256 Days

Coupled with	Average Corrosion Penetration in 10^{-4} cm, When Stored in 5000 ppm NaCl, days								pH 5, days							
	2	4	8	16	32	64	128	256	2	4	8	16	32	64	128	256
Complete Immersion																
Spring steel	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	12
Alumoweld	1	1	1	1	2	4	19	30	0	0	0	0	1	2	5	17
Normal penetration	0	0	0	1	2	6	15	38	0	1	1	-	8	8	13	45*
Partial Immersion																
Spring steel	1	1	1	1	2	2	3	6**	0	0	0	1	1	1	2	2
Alumoweld	1	1	1	1	2	11	30	65	0	0	1	1	3	2	7	26
Normal penetration	1	1	3*	3	12	22	42	--	1	1	1*	3	8	15	33	--
Alternate Immersion and Drying																
Spring steel	0	1	1	2	3	5	12	18	1	1	1	1	2	2	4	12
Alumoweld	0	1	1	1	2	1	4	16	1	1	1	1	1	1	2	10
Normal penetration	0	1	1	1	3	6	8	18	1	1	1	-	2	2†	4	7††

* Average of 6 specimens.
** Average of 2 specimens.
† Average of 4 specimens.
†† Average of 5 specimens.

Table 8

Average Galvanic Effect on Corrosion Rate of Copperweld of Storage in NaCl and pH 5 Solutions for 2 to 256 Days

Coupled with	Average Corrosion Penetration in 10^{-4} cm, When Stored in 5000 ppm NaCl, days								pH 5, days							
	2	4	8	16	32	64	128	256	2	4	8	16	32	64	128	256
Complete Immersion																
Spring steel	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	4
Alumoweld	1	1	1	1	0	3	4	21	0	0	0	0	1	3	6	23
Normal penetration	0	0	1	1	2	5	13	42	1	1	1	-	8	7	19	43*
Partial Immersion																
Spring steel	1	1	1	1	1	1	2	6	0	0	0	1	1	1	2	3
Alumoweld	1	1	1	1	2	7	29	52	0	0	0	1	2	4	8	10
Normal penetration	1	1	2*	6	13	24	54	--	1	1	1*	3	7	13	28	--
Alternate Immersion and Drying																
Spring steel	0	0	1	1	2	7	10	17	1	0	1	1	2	3	4	13
Alumoweld	0	0	0	1	1	1	3	17	1	1	1	1	1	1	2	10
Normal penetration	0	0	0	1	2	5	8	12	1	1	1	-	2	2**	3	8†

* Average of 6 specimens.
** Average of 4 specimens.
† Average of 5 specimens.

Table 9

Average Galvanic Effect on Corrosion Rate of Spring Steel of Storage in NaCl and pH 5 Solutions for 2 to 256 Days

Coupled with	Average Corrosion Penetration in 10^{-4} cm, When Stored in 5000 ppm NaCl, days								pH 5, days							
	2	4	8	16	32	64	128	256	2	4	8	16	32	64	128	256
Complete Immersion																
Alumoweld	4	4	4	3	6	8	21	39	1	1	2	3	5	13	22	50
Copperply	6	7	6	6	11	20	50	85	1	2	3	3	7	16	29	69
Copperweld	5	6	6	5	11	19	45	75	2	2	2	4	7	17	26	53
Normal penetration	1	2	2	2	6	10	25	70	2	2	3	-	14	13	32	77*
Partial Immersion																
Alumoweld	4	3	4	2	7	27	50	119	1	2	3	5	13	23	43	93
Copperply	5	6	9	12	24	58	134	229**	2	3	4	9	22	35	70	143
Copperweld	4	5	7	12	23	55	133	221	2	3	5	10	24	40	67	146
Normal penetration	2	2	7*	8	20	40	93	---	2	2	7*	7	15	32	72	---
Alternate Immersion and Drying																
Alumoweld	4	7	6	14	15	27	232	285	3	5	14	21	41	76	143	290
Copperply	6	10	14	13	18	183	368	451	5	6	17	23	33	60	132	253
Copperweld	6	11	11	16	24	168	362	477	4	5	13	20	32	71	125	288
Normal penetration	3	6	8	25	54	173	331	752	2	4	11	--	55	54†	130	220††

* Average of 6 specimens.
** Average of 2 specimens.
† Average of 4 specimens.
†† Average of 5 specimens.

Table 10

Effect of Pinhole on Average Corrosion Penetration of Specimens Stored in 5000 ppm NaCl Solution

Storage Condition	Average Corrosion Penetration in 10^{-4} cm After Indicated Time in Days							
	2	4	8	16	32	64	128	256
Spring Steel								
Partial immersion, 0.021-in. hole	2	2	4	9	12	20	53	119
Partial immersion, no hole	2	2	7*	8	20	40	93	---
Alternate immersion, 0.021-in. hole	4	6	10	12	16	189	411	465
Alternate immersion, no hole	3	6	8	25	54	173	331	752
Copperply								
Partial immersion, 0.021-in. hole	1	1	1	2	6	7	22	51
Partial immersion, no hole	1	1	3*	3	12	22	42	--
Alternate immersion, 0.021-in. hole	1	1	1	2	3	7	11	16
Alternate immersion, no hole	0	1	1	1	3	6	8	18
Copperweld								
Partial immersion, 0.021-in. hole	0	1	2	2	6	7	21	49
Partial immersion, no hole	1	1	2*	6	13	24	54	--
Alternate immersion, 0.021-in. hole	1	1	2	2	3	6	11	12
Alternate immersion, no hole	0	0	0	1	2	5	8	12
Alumoweld								
Partial immersion, 0.021-in. hole	1	2	2	3	5	6	16	34
Partial immersion, no hole	2	3	7*	3	5	5	9	--
Alternate immersion, 0.021-in. hole	1	2	2	2	3	13	17	27
Alternate immersion, no hole	0	0	1	1	4	7	10	16

* Average of 6 specimens.

Table 11

Effect of Pinhole on Average Corrosion Penetration of Specimens Stored in pH 5 Solution

Storage Condition	Average Corrosion Penetration in 10^{-4} cm After Indicated Time in Days: 2	4	8	16	32	64	128	256
Spring Steel								
Partial immersion, 0.021-in. hole	1	1	2	5	13	25	48	100
Partial immersion, no hole	2	2	7*	7	15	32	72	---
Alternate immersion, 0.021-in. hole	3	6	8	13	27	65	177	278
Alternate immersion, no hole	2	4	11	--	55	54**	130	220†
Copperply								
Partial immersion, 0.021-in. hole	0	0	1	1	2	6	13	28
Partial immersion, no hole	1	1	1*	3	8	15	33	--
Alternate immersion, 0.021-in. hole	0	1	1	1	1	2	4	16
Alternate immersion, no hole	1	1	1	-	2	2**	4	7†
Copperweld								
Partial immersion, 0.021-in. hole	0	0	0	1	2	4	11	24
Partial immersion, no hole	1	1	1*	3	7	13	28	--
Alternate immersion, 0.021-in. hole	0	0	1	1	2	3	5	16
Alternate immersion, no hole	1	1	1	-	2	2**	3	8†
Alumoweld								
Partial immersion, 0.021-in. hole	1	1	1	2	4	6	15	41
Partial immersion, no hole	4	3	3*	4	3	4	7	--
Alternate immersion, 0.021-in. hole	1	2	1	1	1	2	4	15
Alternate immersion, no hole	3	2	2	-	5	2**	8	7†

* Average of 6 specimens.
** Average of 4 specimens.
† Average of 5 specimens.

Table 12

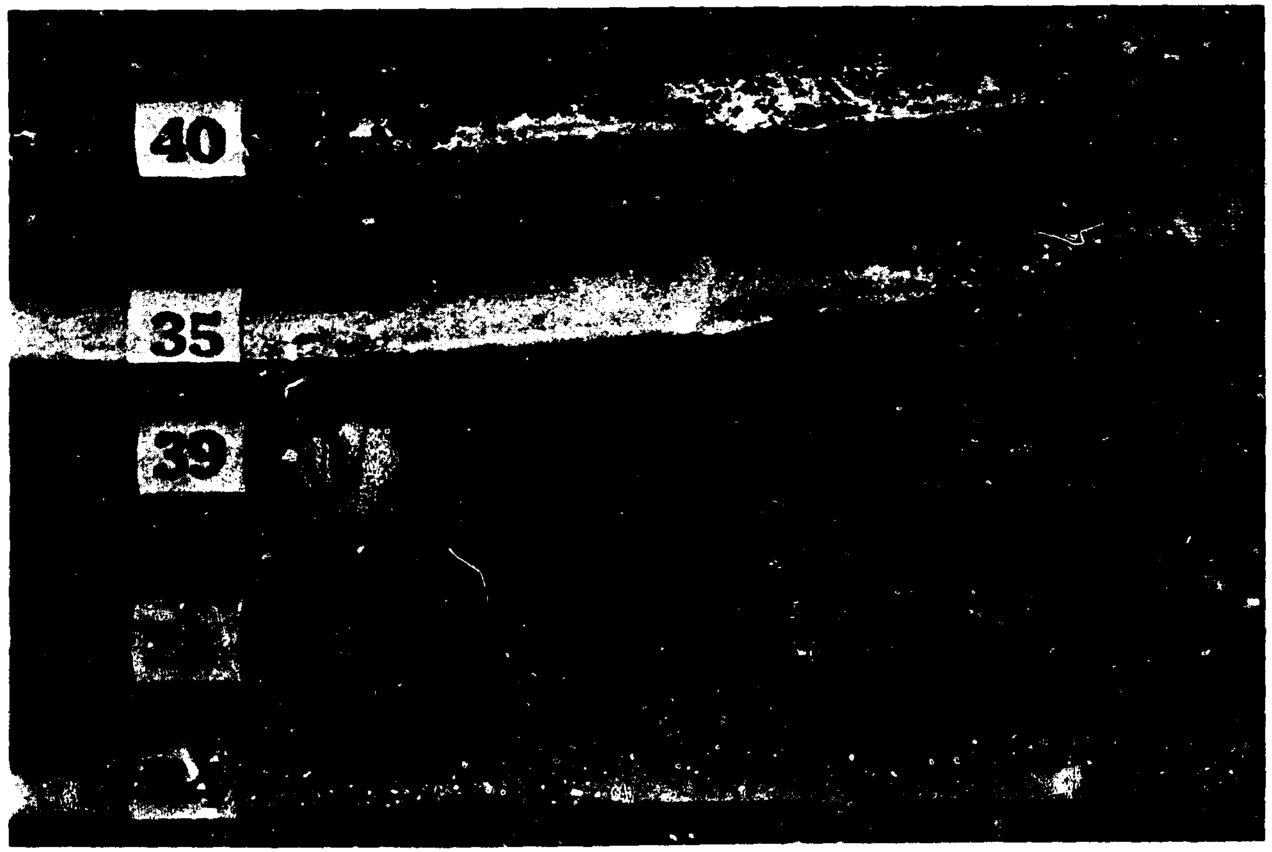
Average Coating Loss Due to Abrasion in 10^{-4} cm

Wire	Time, days 1	3	7
Abraded with a Slurry of Natural Siliceous Sand Passing the No. 50 Sieve and Retained on the No. 100			
Alumoweld	0.30	0.51	1.00
Copperweld	0.05	0.15	0.21
Copperply	0.06	0.11	0.22
Abraded with a Slurry of Natural Siliceous Sand Passing the No. 100 Sieve			
Alumoweld	0.39	0.71	1.35
Copperweld	0.16	0.35	0.90
Copperply	0.17	0.33	0.63

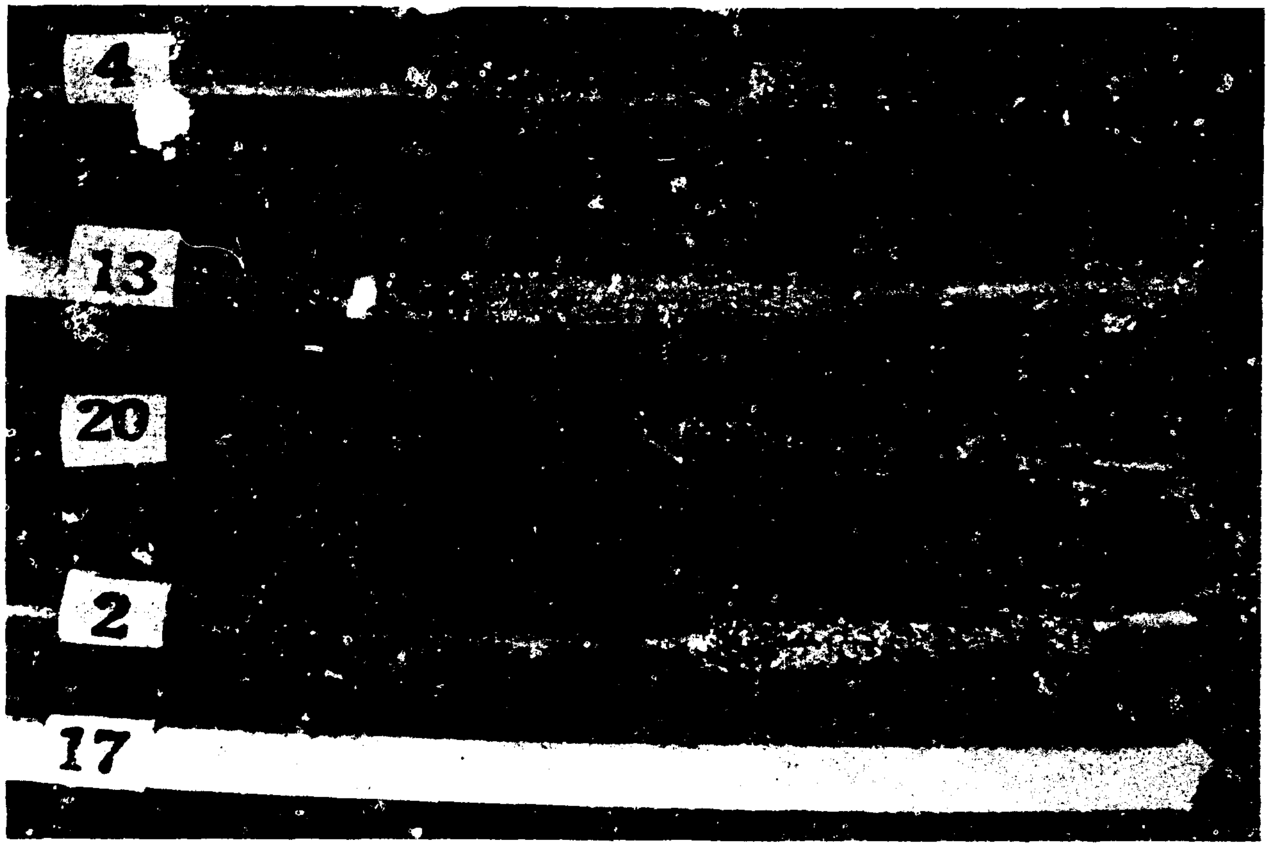
Table 13

Summary of Water Analyses of the Mississippi River

Constituent		New Orleans, La. Municipal Water Plant Intake	Luling Ferry, La. Luling-to-Destrehan Crossing	Baton Rouge, La. Above Bridge on U. S. Hwy 190	St. Francisville, La. Ferry on State Hwy 10	Vicksburg, Miss. Municipal Water Plant Intake	Vicksburg, Miss. Delta Point USCE Casting Yard	West Memphis, Ark. Barge Terminal Okla.-Miss. R. Prod. Line	Cape Girardeau, Mo. Mo. Utilities Co. Water Intake	St. Louis, Mo. E. St. Louis Water Co., Ill Intake	St. Louis, Mo. MacArthur Bridge
pH scale units	Average	[illegible]	7.8	7.1	7.7	7.4	7.4	7.7	7.7	7.7	7.2
	Maximum	[illegible]	8.1	7.7	8.1	7.7	8.2	8.1	8.1	8.5	7.7
	Minimum	[illegible]	[illegible]	6.9	7.3	7.1	6.6	7.3	7.5	7.2	6.8
	No. of tests	127	36	4	71	39	71	122	91	90	12
Alkalinity ppm	Average	[illegible]	---	---	---	68	101	96	129	151	---
	Maximum	150	---	---	---	124	141	134	202	212	---
	Minimum	73	---	---	---	42	72	52	78	82	---
	No. of tests	127	---	---	---	39	[illegible]	122	91	90	---
Turbidity scale units	Average	[illegible]	---	---	---	169	260	335	410	219	---
	Maximum	1500	---	---	---	700	925	1400	1720	1500	---
	Minimum	[illegible]	---	---	---	85	95	20	65	25	---
	No. of tests	127	---	---	---	39	63	120	91	90	---
Total dissolved solids ppm	Average	[illegible]	239	205	219	---	221	234	272	256	276
	Maximum	308	293	255	285	---	326	306	346	343	444
	Minimum	166	175	160	152	---	105	158	216	131	171
	No. of tests	95	36	4	71	---	69	96	5	52	9
Cl, ppm	Average	25	26	16	20	13	21	13	20	16	10
	Maximum	55	35	17	35	28	38	29	32	28	20
	Minimum	12	16	15	12	0	10	6	7	11	5
	No. of tests	127	36	4	71	39	70	122	60	90	12
SO_4, ppm	Average	47	52	42	46	---	43	45	104	56	69
	Maximum	67	73	55	69	---	64	31	142	75	153
	Minimum	32	35	28	28	---	21	26	64	33	34
	No. of tests	95	36	4	71	---	71	97	5	52	12
SiO_2, ppm	Average	---	9	6	10	---	---	---	---	---	10
	Maximum	---	12	8	13	---	---	---	---	---	13
	Minimum	---	6	5	5	---	---	---	---	---	9
	No. of tests	---	36	4	71	---	---	---	---	---	9
Fe ppm	Average	---	0.07	0.05	0.06	---	---	---	---	---	0.01
	Maximum	---	0.23	0.08	0.37	---	---	---	---	---	0.02
	Minimum	---	0.01	0.02	0	---	---	---	---	---	0.01
	No. of tests	---	36	4	68	---	---	---	---	---	9
Ca, ppm	Average	---	42	35	39	---	---	---	---	---	47
	Maximum	---	53	41	50	---	---	---	---	---	65
	Minimum	---	31	26	27	---	---	---	---	---	35
	No. of tests	---	36	4	71	---	---	---	---	---	9
Mg, ppm	Average	---	11	9	10	---	---	---	---	---	14
	Maximum	---	19	[illegible]	14	---	---	---	---	---	19
	Minimum	---	6	6	4	---	---	---	---	---	7
	No. of tests	---	36	4	71	---	---	---	---	---	9
Na, ppm	Average	---	21	14	19	---	---	---	---	---	24
	Maximum	---	34	17	32	---	---	---	---	---	56
	Minimum	---	10	11	11	---	---	---	---	---	7
	No. of tests	---	36	4	71	---	---	---	---	---	9
K ppm	Average	---	2.9	2.9	2.8	---	---	---	---	---	4.1
	Maximum	---	4.1	3.3	4.1	---	---	---	---	---	6.0
	Minimum	---	[illegible]	2.5	2.2	---	---	---	---	---	3.0
	No. of tests	---	36	4	36	---	---	---	---	---	9



Photograph 1. Condition after 32 days of wires cast in mortar cubes and stored at 73 F and 100% relative humidity



Photograph 2. Condition after 32 days of wires cast in mortar cubes and alternately immersed in distilled water for 16 hr, then dried at 100 F for 8 hr

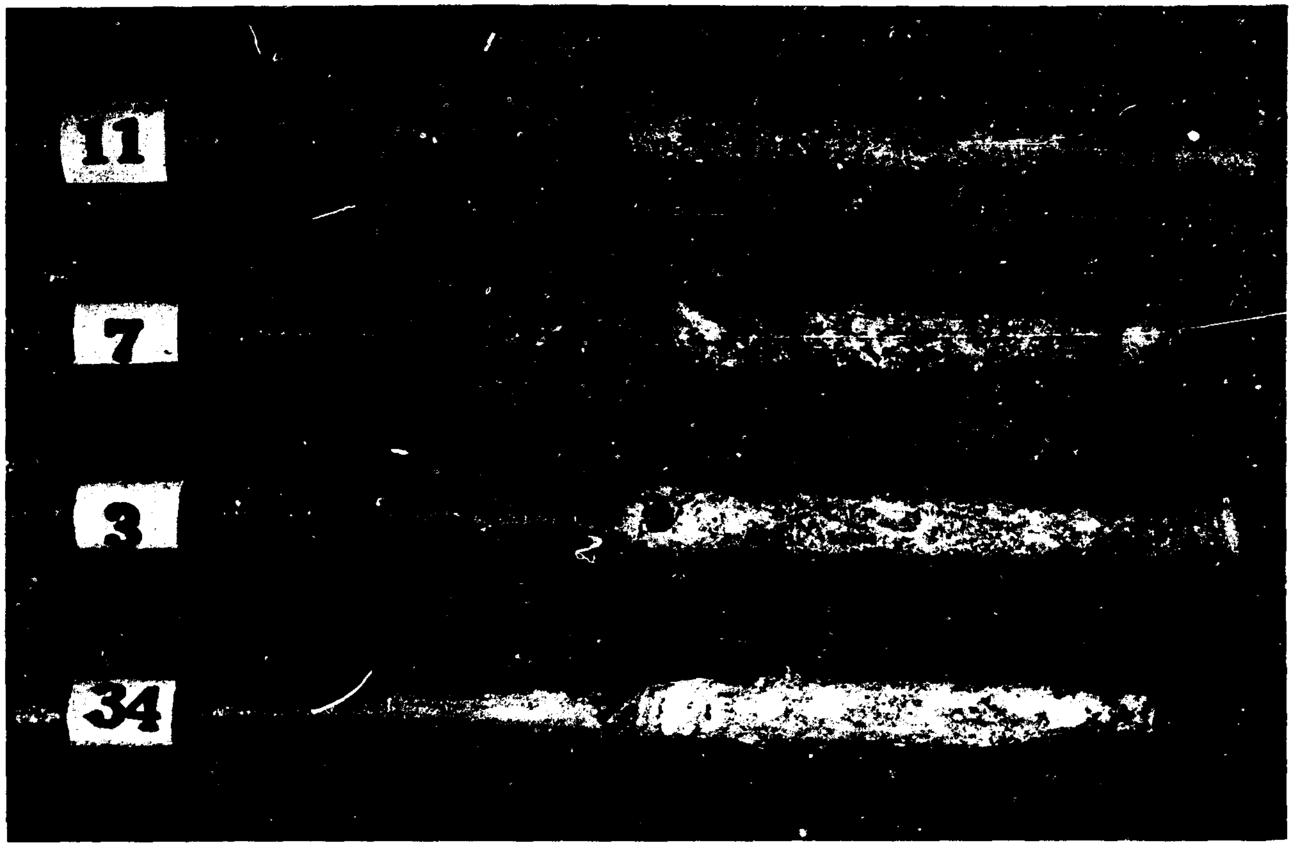
Photograph 3. Condition after 32 days of wires cast in mortar cubes and stored immersed in distilled water at 100 F

2 days

4 days

8 days

32 days



Photograph 4. Effect of exposure time on alumoweld wires cast in mortar cubes and stored in air at 73 F and 100% relative humidity

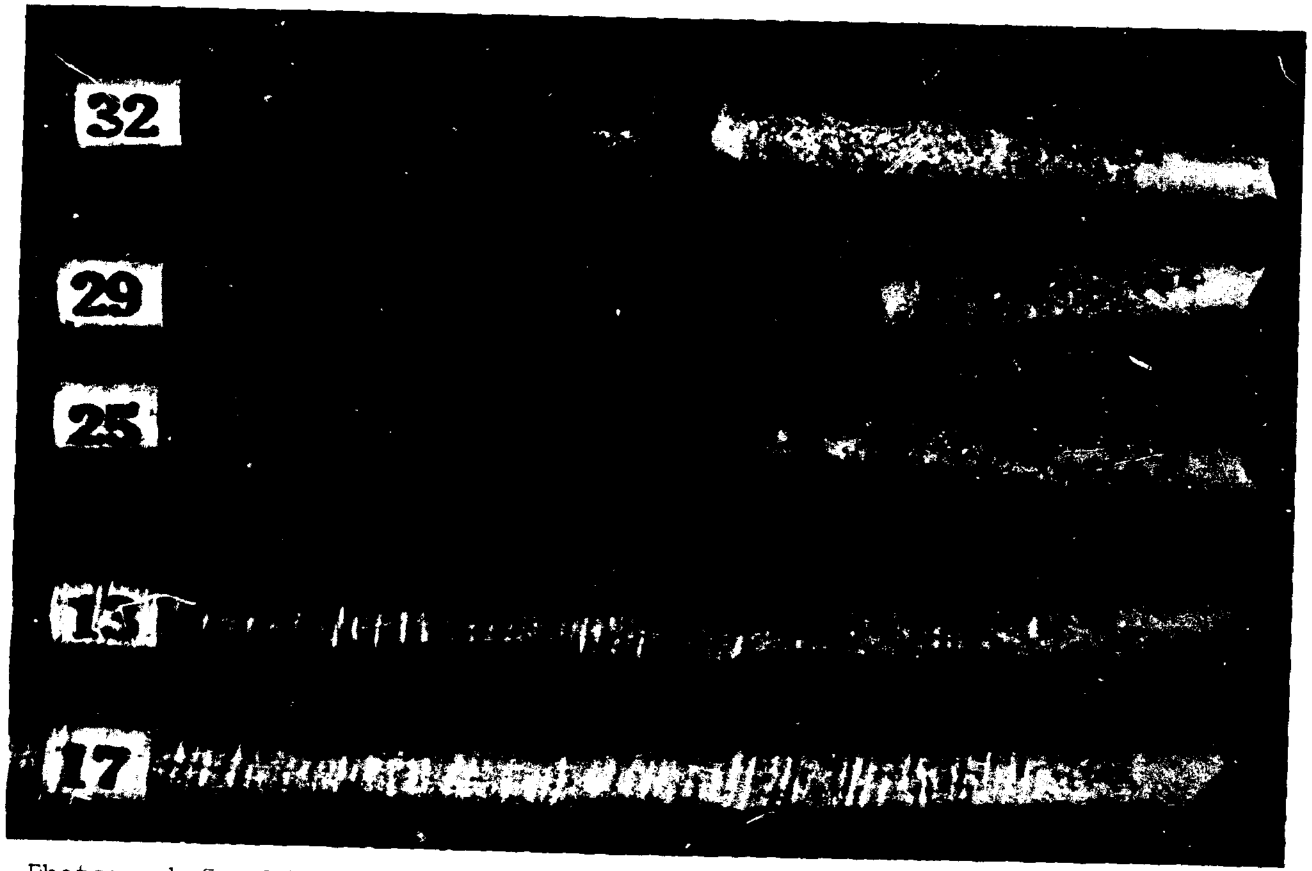
2 days

4 days

8 days

16 days

32 days



Photograph 5. Effect of exposure time on alumoweld wires cast in mortar cubes and alternately wetted, then dried at 100 F

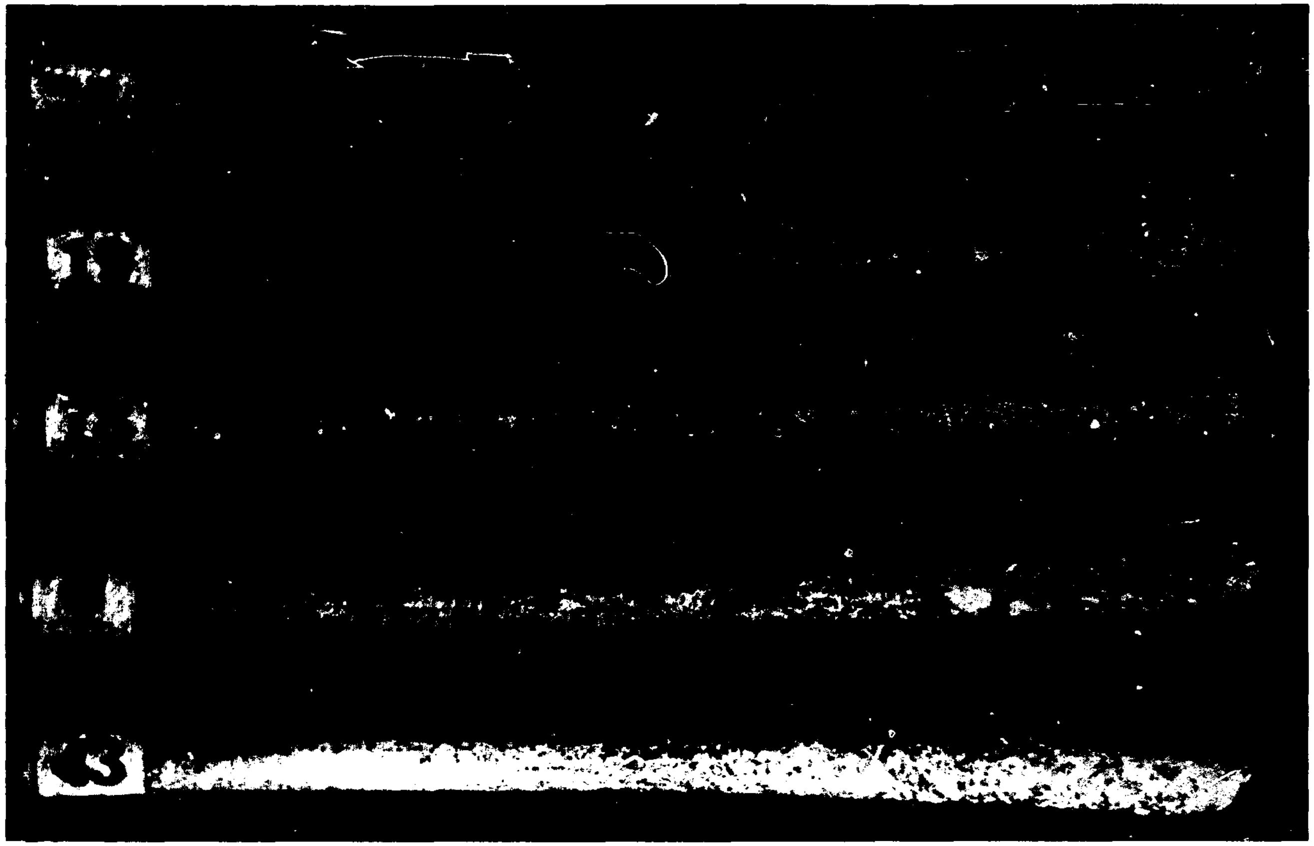
2 days

4 days

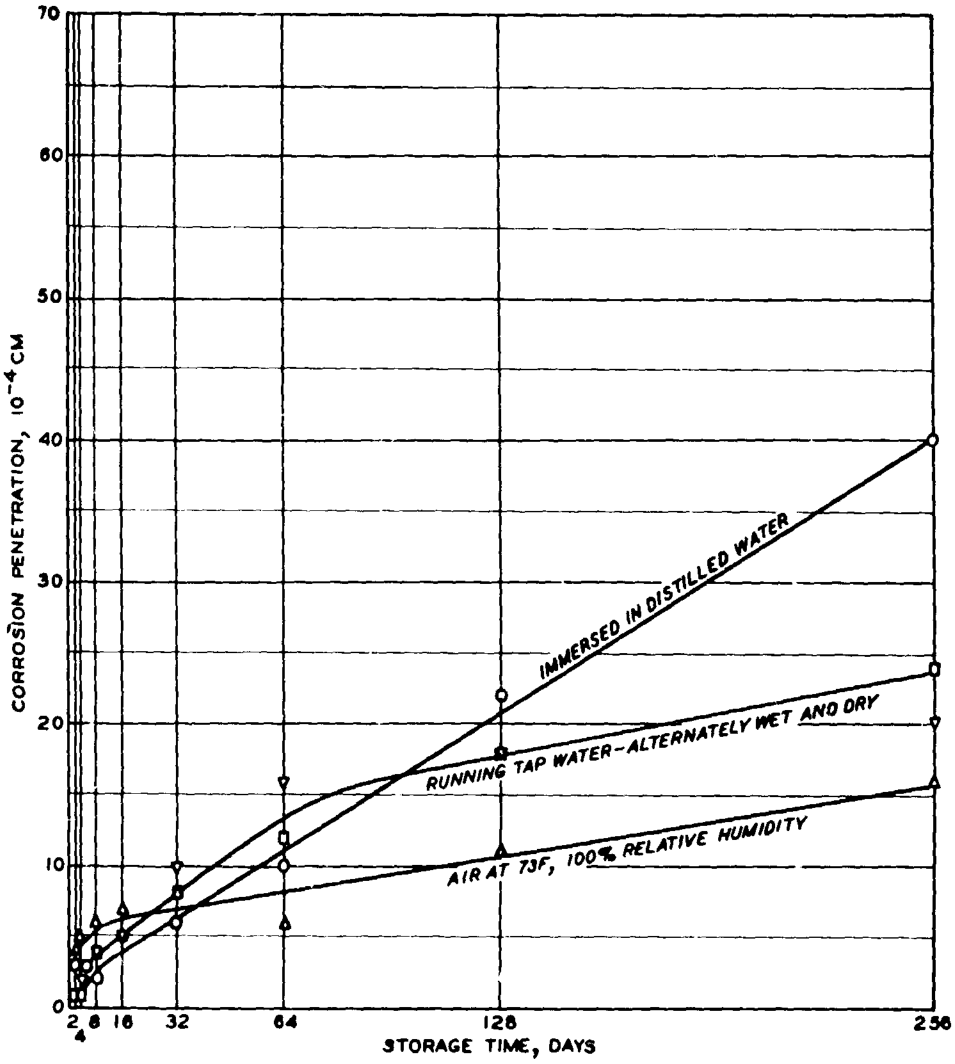
8 days

16 days

32 days



Photograph 6. Effect of exposure time on alumoweld wires cast in mortar cubes and stored immersed in distilled water at 100 F



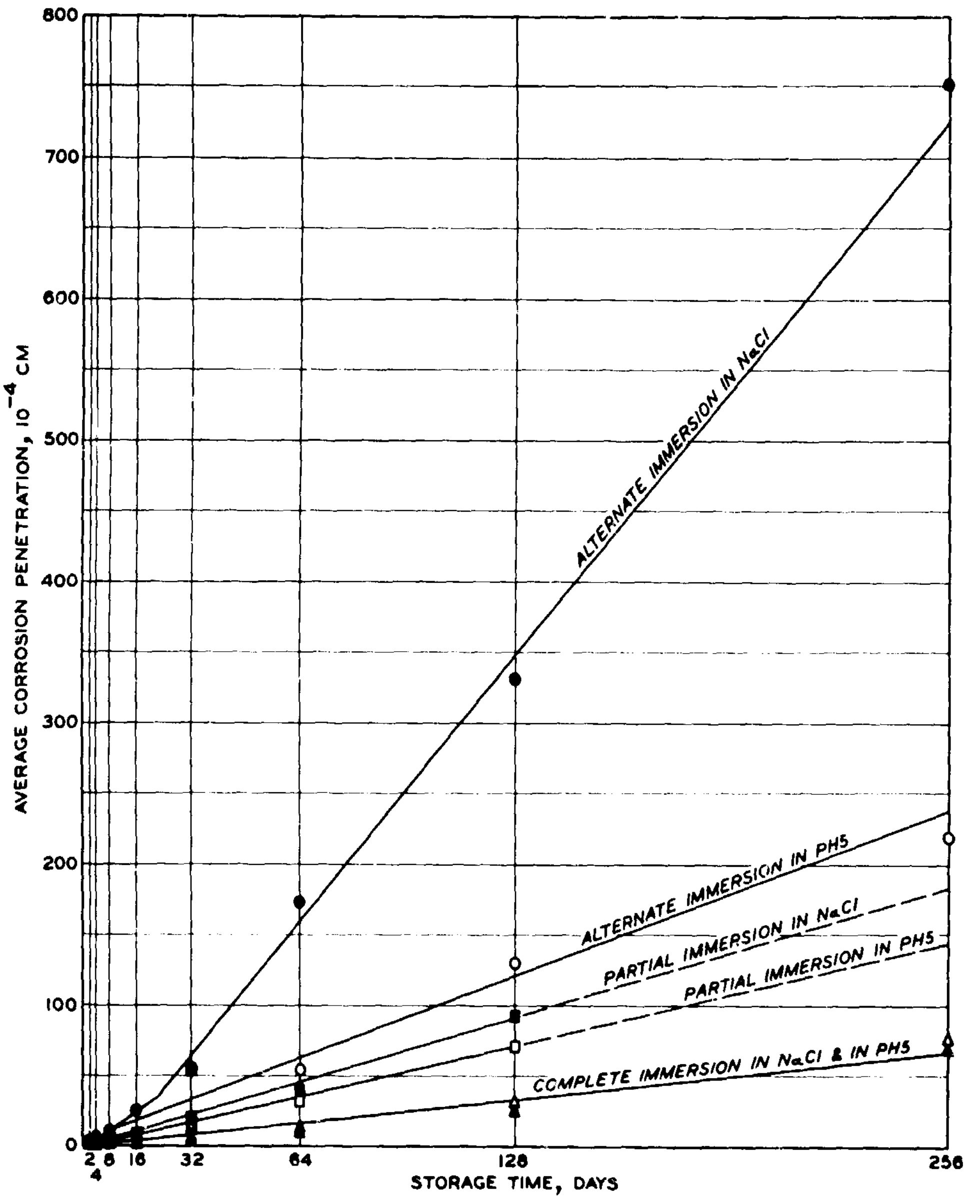
LEGEND

- △ AIR AT 73 F AND 100% RELATIVE HUMIDITY
- O IMMERSED IN DISTILLED WATER
- ▽ ALTERNATELY WET AND DRY*
- □ UNDER RUNNING TAP WATER

NOTE: * ALTERNATELY IMMERSED IN DISTILLED WATER FOR 16 HOURS AND DRIED IN AIR AT 100 F FOR 8 HOURS.

CORROSION PENETRATION RATE

SPRING STEEL WIRE PARTLY EMBEDDED IN MORTAR CUBES



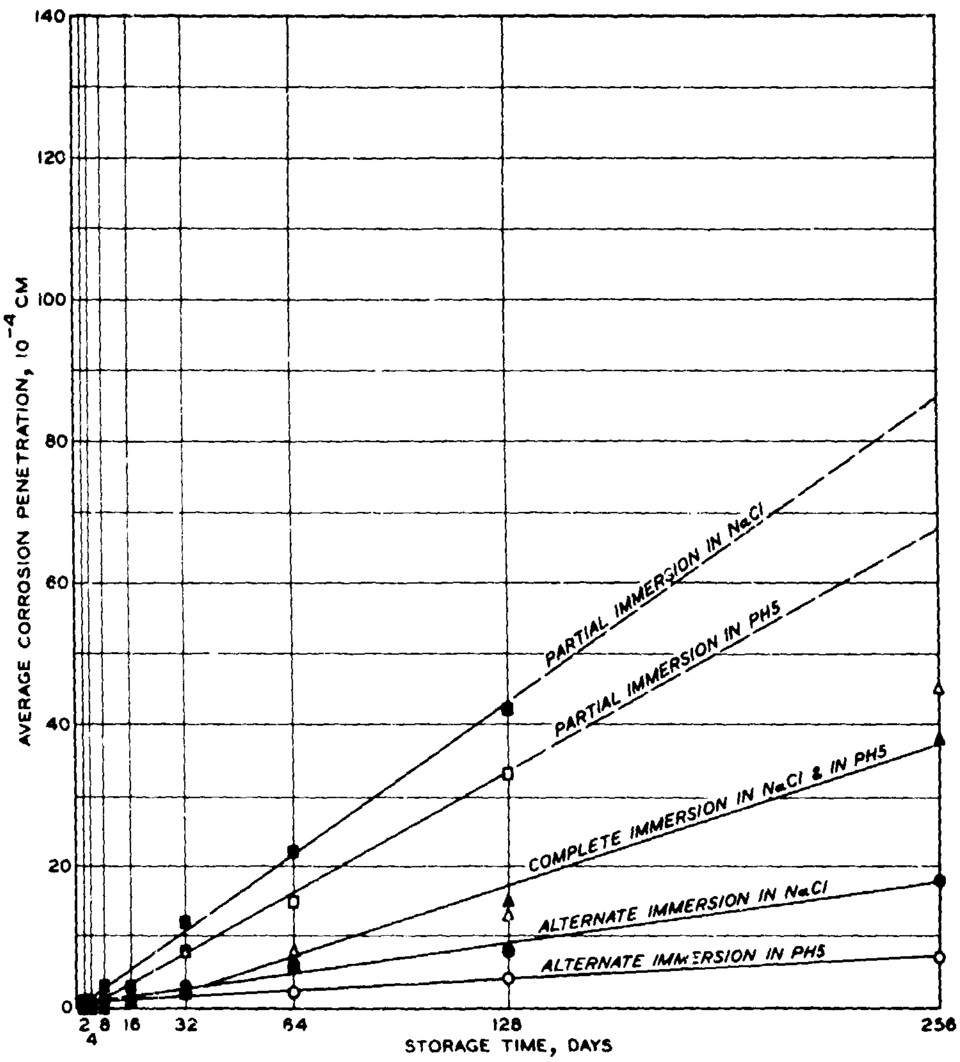
LEGEND

- ● ALTERNATE IMMERSION IN NaCl
- ○ ALTERNATE IMMERSION IN PH5
- ■ PARTIAL IMMERSION IN NaCl
- □ PARTIAL IMMERSION IN PH5
- ▲ COMPLETE IMMERSION IN NaCl
- △ COMPLETE IMMERSION IN PH5

NOTE: IN PLATES 2–14, ALTERNATE IMMERSION DENOTES REPEATED CYCLES OF COMPLETE IMMERSION IN THE TEST SOLUTION FOR ONE HOUR, THEN DRYING IN AIR AT 100 F FOR ONE HOUR.

CORROSION PENETRATION RATE

SPRING STEEL WIRE IMMERSED IN NaCl AND PH5 SOLUTIONS

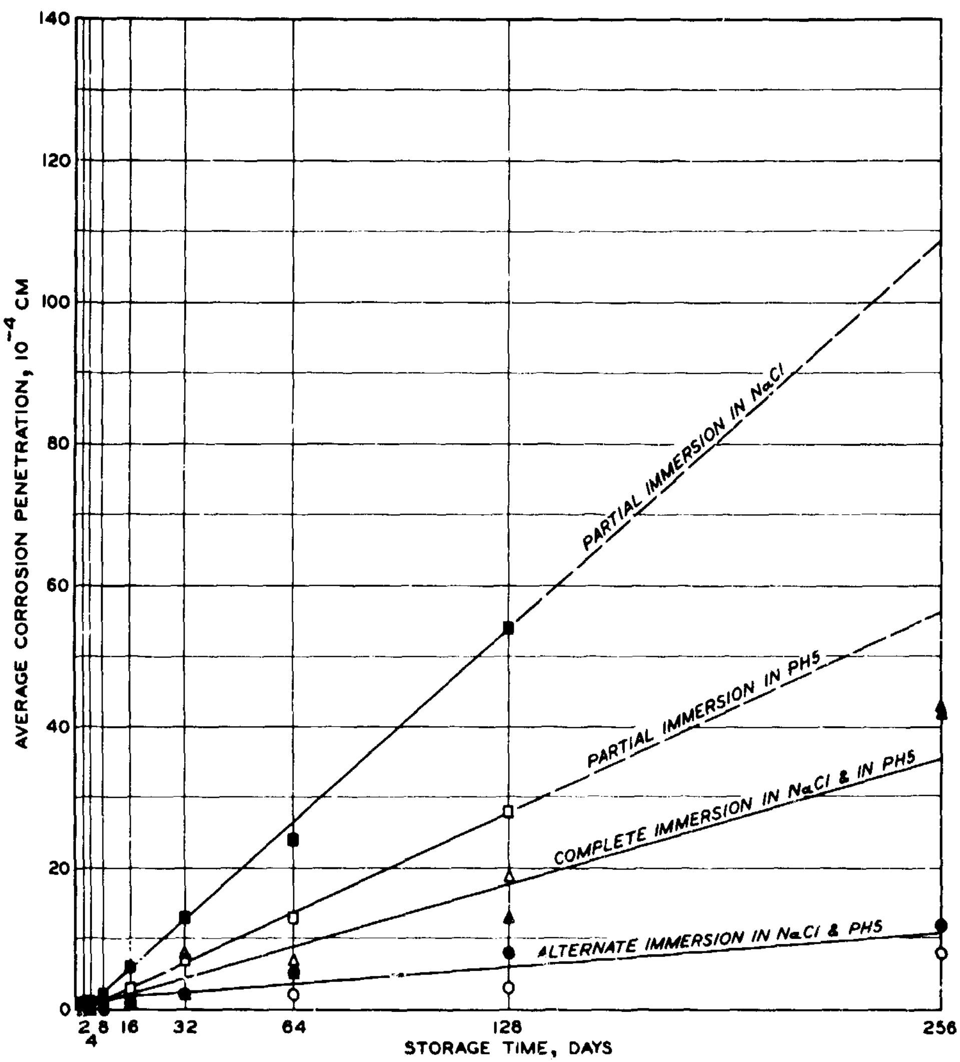


LEGEND

- ● ALTERNATE IMMERSION IN NaCl
- ○ ALTERNATE IMMERSION IN PH5
- ■ PARTIAL IMMERSION IN NaCl
- □ PARTIAL IMMERSION IN PH5
- ▲ COMPLETE IMMERSION IN NaCl
- △ COMPLETE IMMERSION IN PH5

CORROSION PENETRATION RATE

COPPERPLY IMMERSED IN NaCl AND PH5 SOLUTIONS

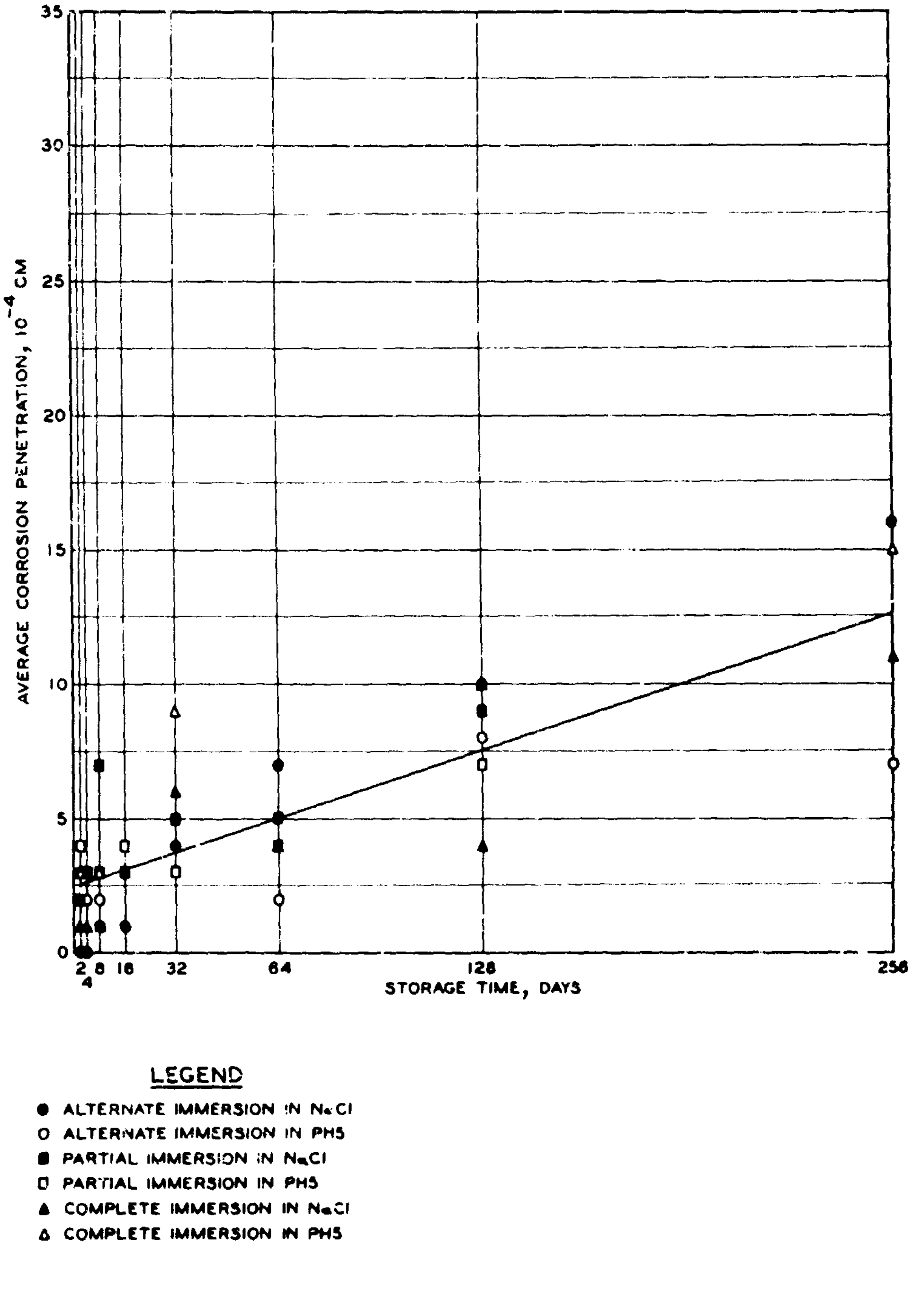


LEGEND

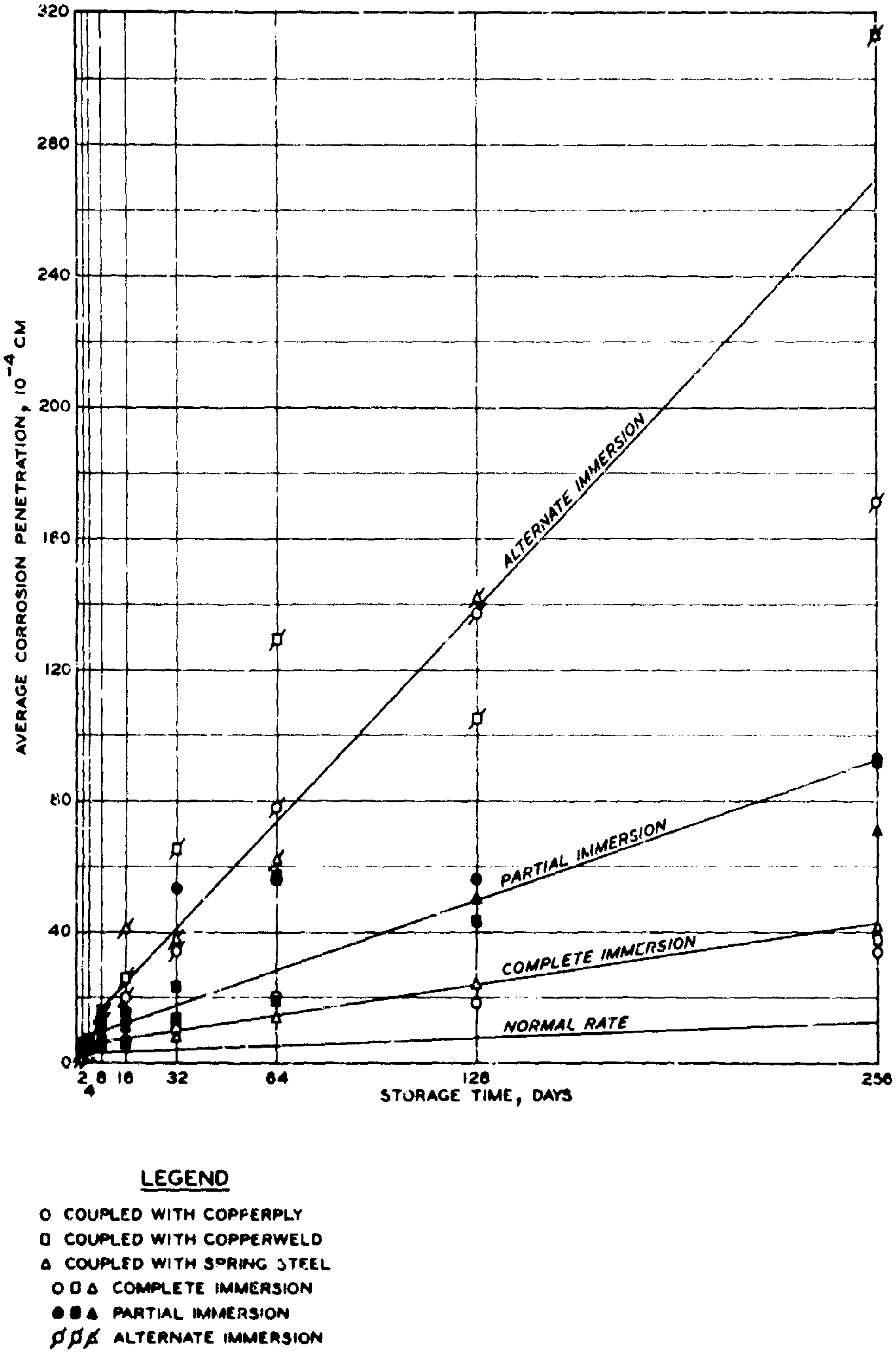
● ALTERNATE IMMERSION IN NaCl
○ ALTERNATE IMMERSION IN PH5
■ PARTIAL IMMERSION IN NaCl
□ PARTIAL IMMERSION IN PH5
▲ COMPLETE IMMERSION IN NaCl
△ COMPLETE IMMERSION IN PH5

CORROSION
PENETRATION RATE
COPPERWELD IMMERSED IN
NaCl AND PH5 SOLUTIONS

PLATE 4



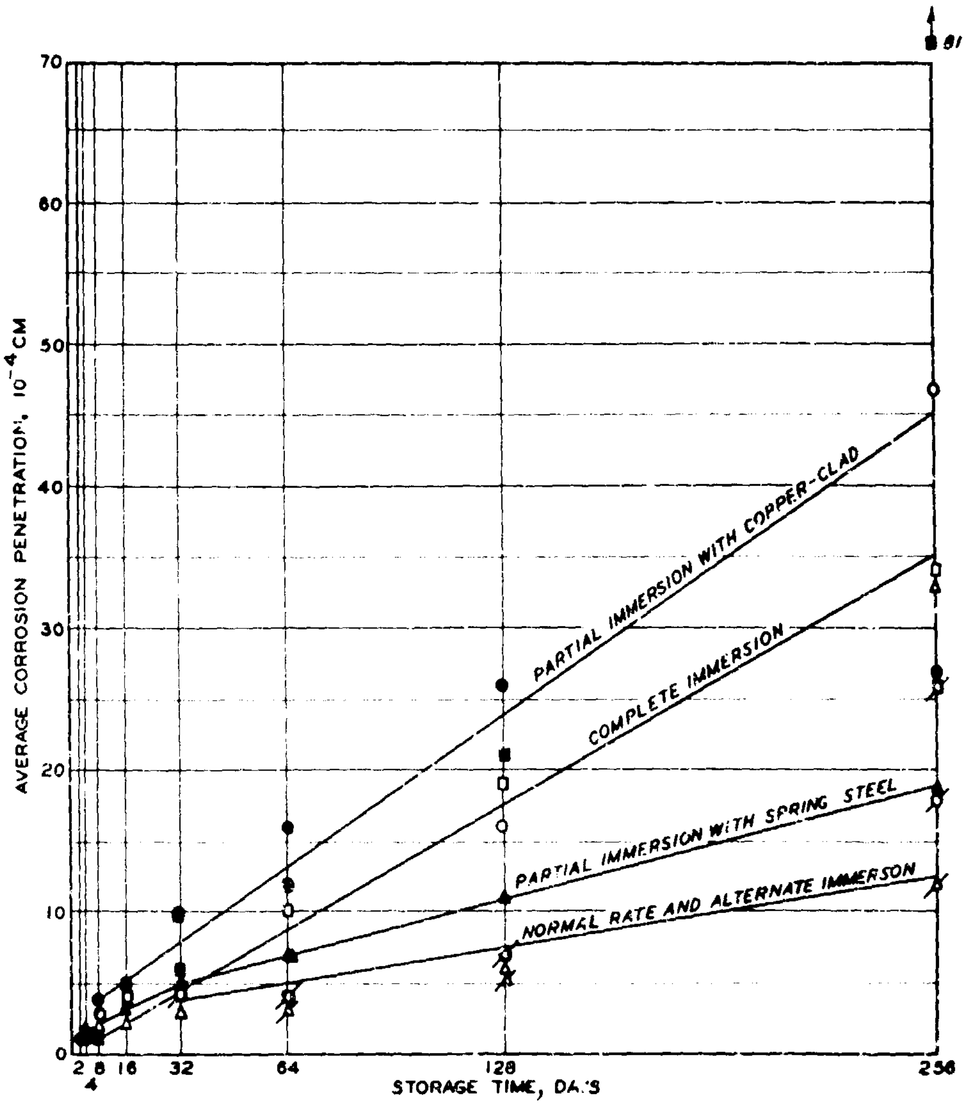
CORROSION
PENETRATION RATE
ALUMOWELD IMMERSED IN
NaCl AND PH5 SOLUTIONS



GALVANIC EFFECT ON CORROSION RATE

ALUMOWELD IMMERSED IN 5000 PPM NaCl SOLUTION

PLATE 6

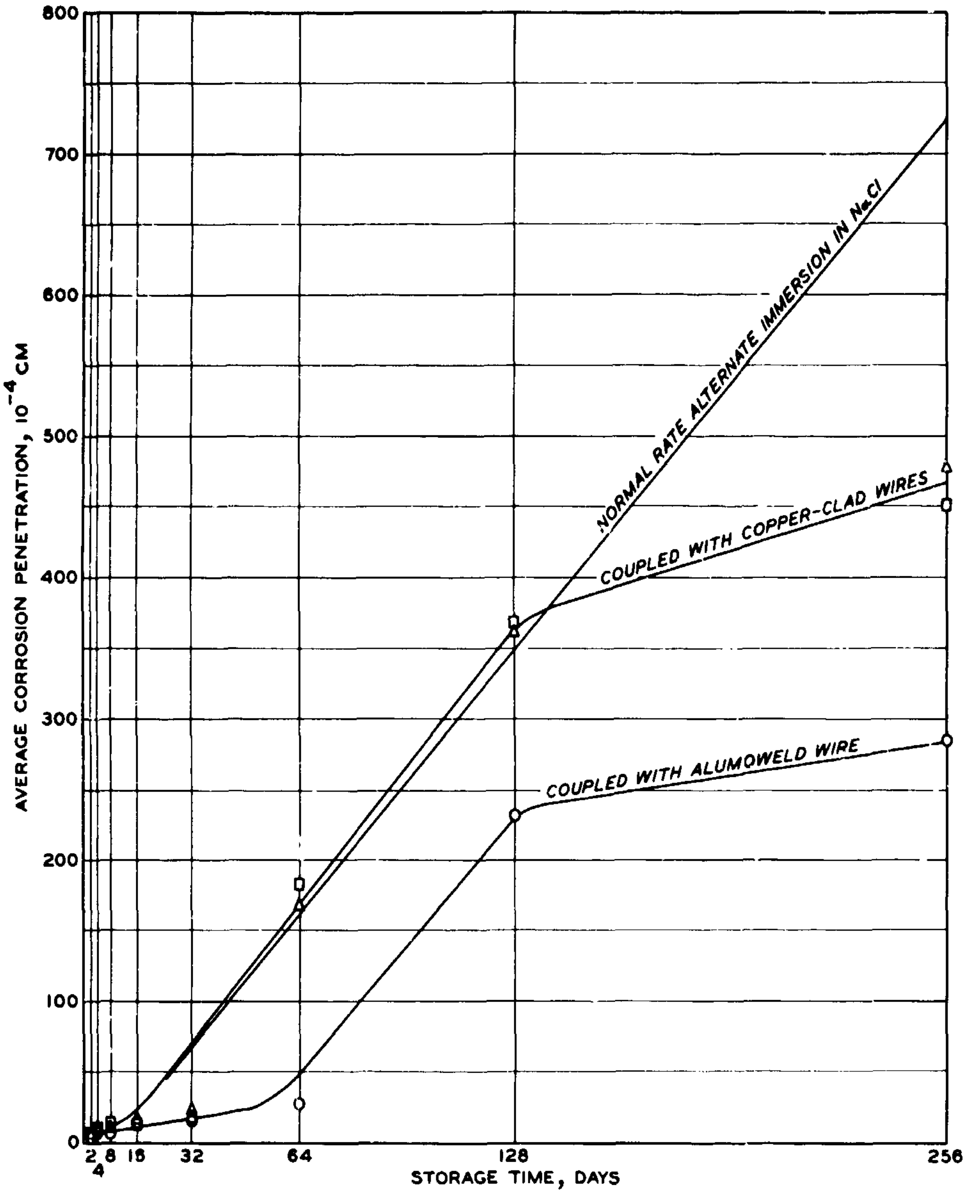


LEGEND

O COUPLED WITH COPPERPLY
□ COUPLED WITH COPPERWELD
Δ COUPLED WITH SPRING STEEL
O □ Δ COMPLETE IMMERSION
● ■ ▲ PARTIAL IMMERSION
Ø □̸ Δ̸ ALTERNATE IMMERSION

GALVANIC EFFECT ON CORROSION RATE

ALUMOWELD IMMERSED IN PH5 SOLUTION

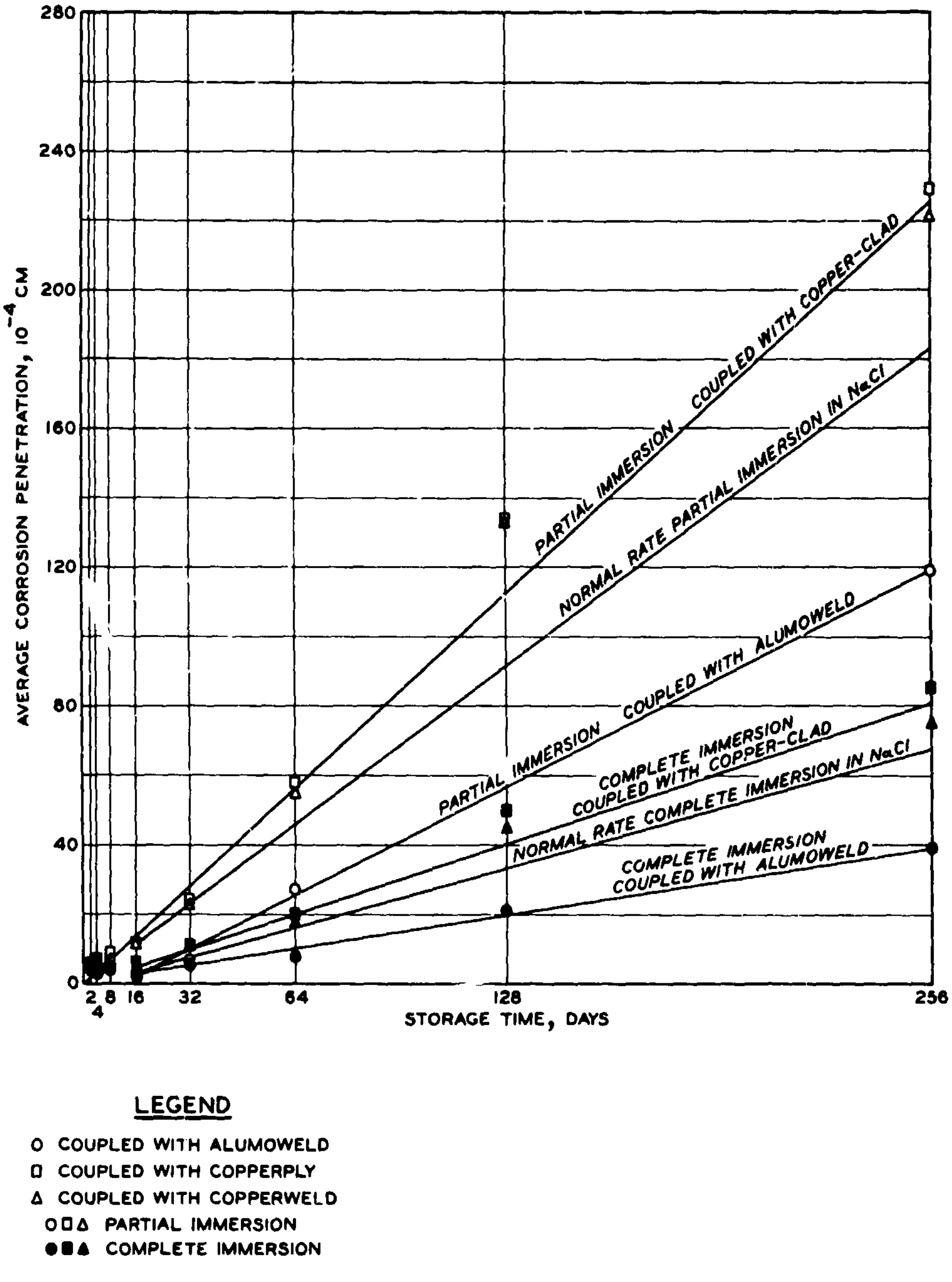


LEGEND

O COUPLED WITH ALUMOWELD
□ COUPLED WITH COPPERPLY
Δ COUPLED WITH COPPERWELD

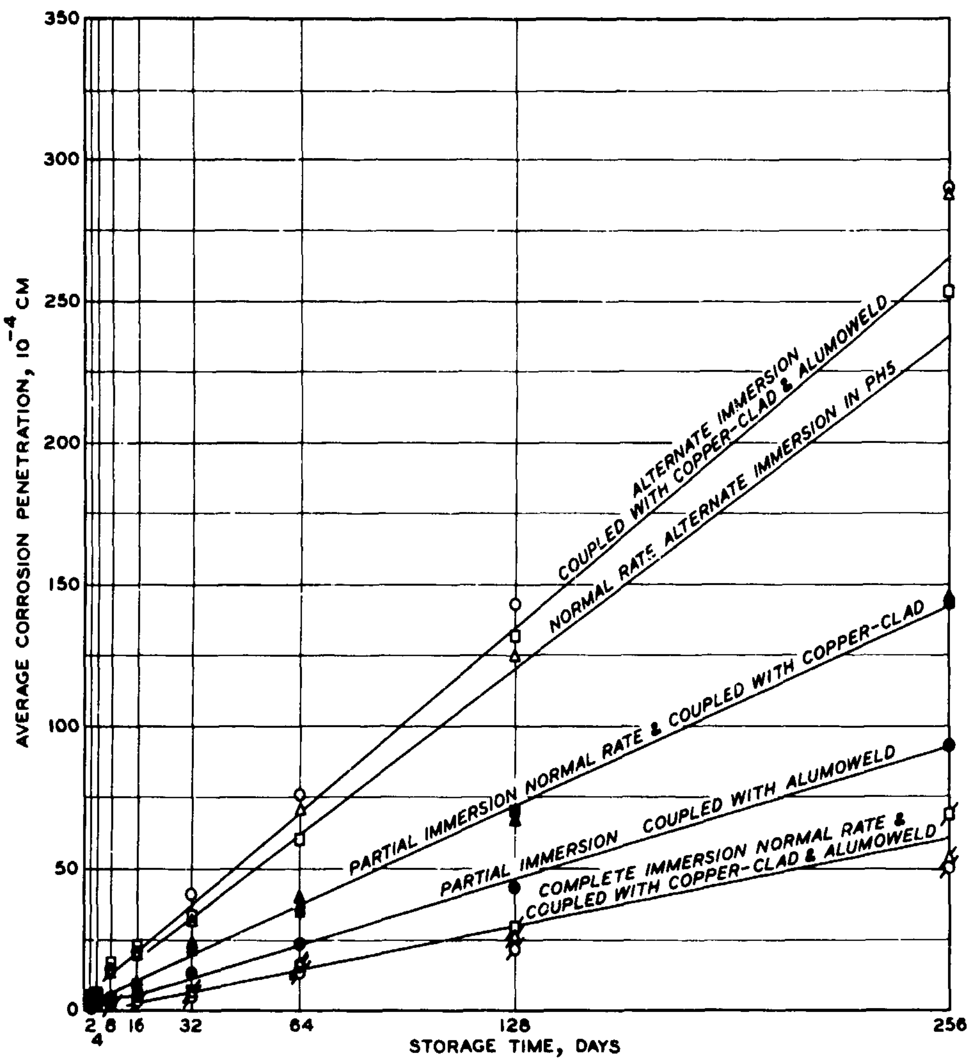
GALVANIC EFFECT ON CORROSION RATE

SPRING STEEL WIRE
ALTERNATELY IMMERSED IN
5000 PPM NaCl SOLUTION



GALVANIC EFFECT ON CORROSION RATE

SPRING STEEL WIRE PARTIALLY AND COMPLETELY IMMERSED IN 5000 PPM NaCl SOLUTION

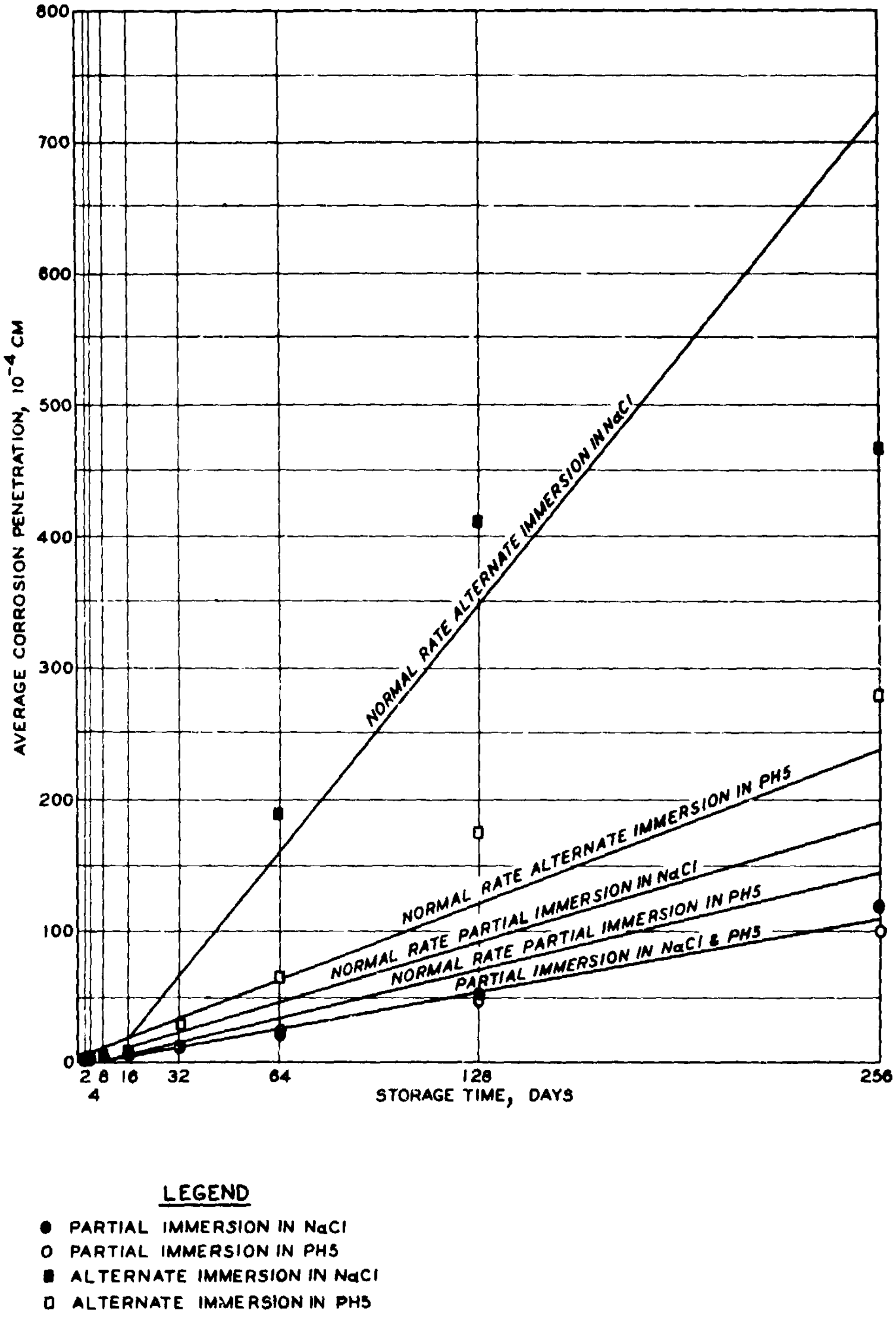


LEGEND

O COUPLED WITH ALUMOWELD
□ COUPLED WITH COPPERPLY
Δ COUPLED WITH COPPERWELD
O □ Δ ALTERNATE IMMERSION
● ■ ▲ PARTIAL IMMERSION
ø ø ø COMPLETE IMMERSION

GALVANIC EFFECT ON CORROSION RATE

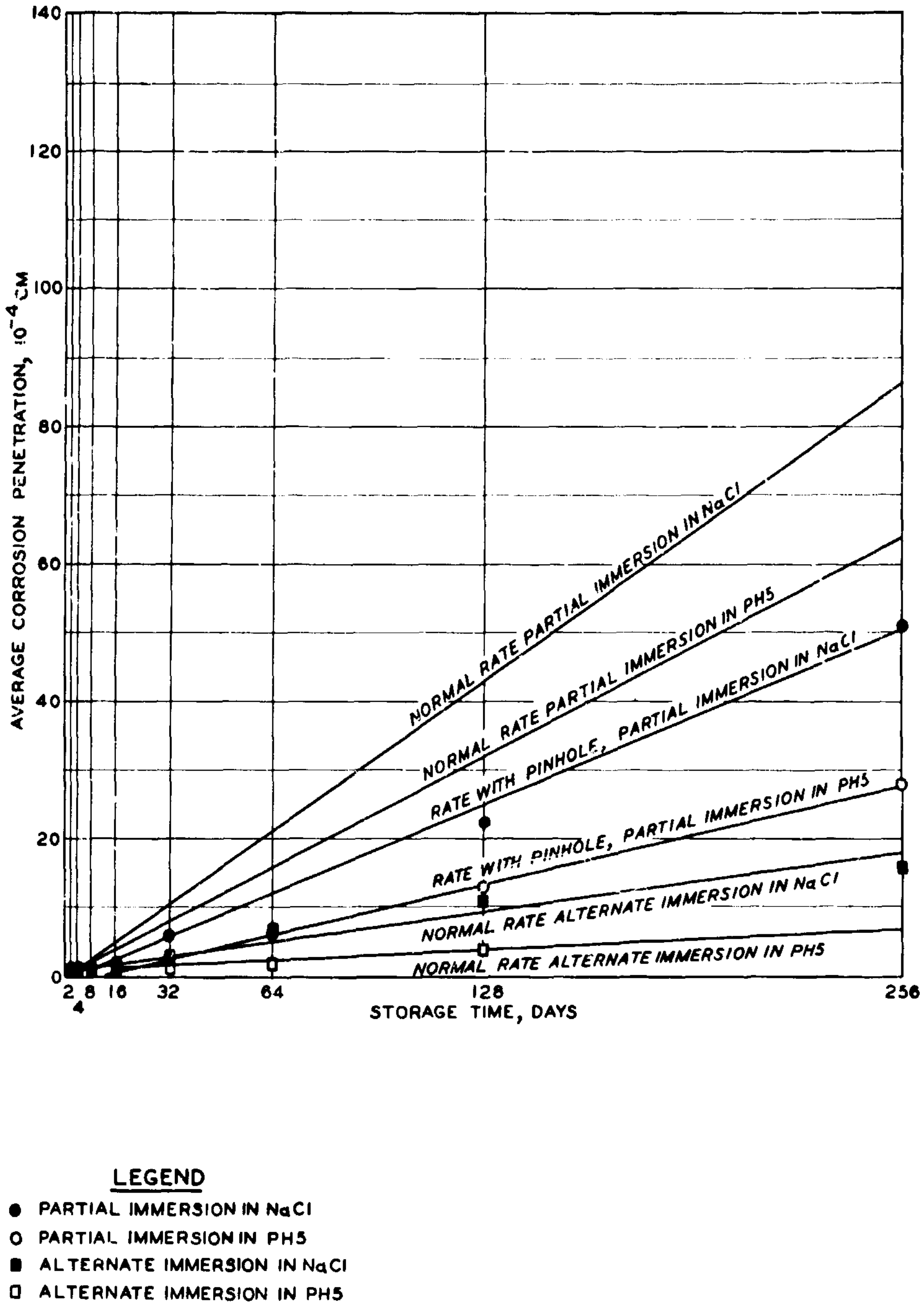
SPRING STEEL WIRE IMMERSED IN PH5 SOLUTION



EFFECT OF 0.021-INCH PINHOLE ON CORROSION RATE

SPRING STEEL WIRE

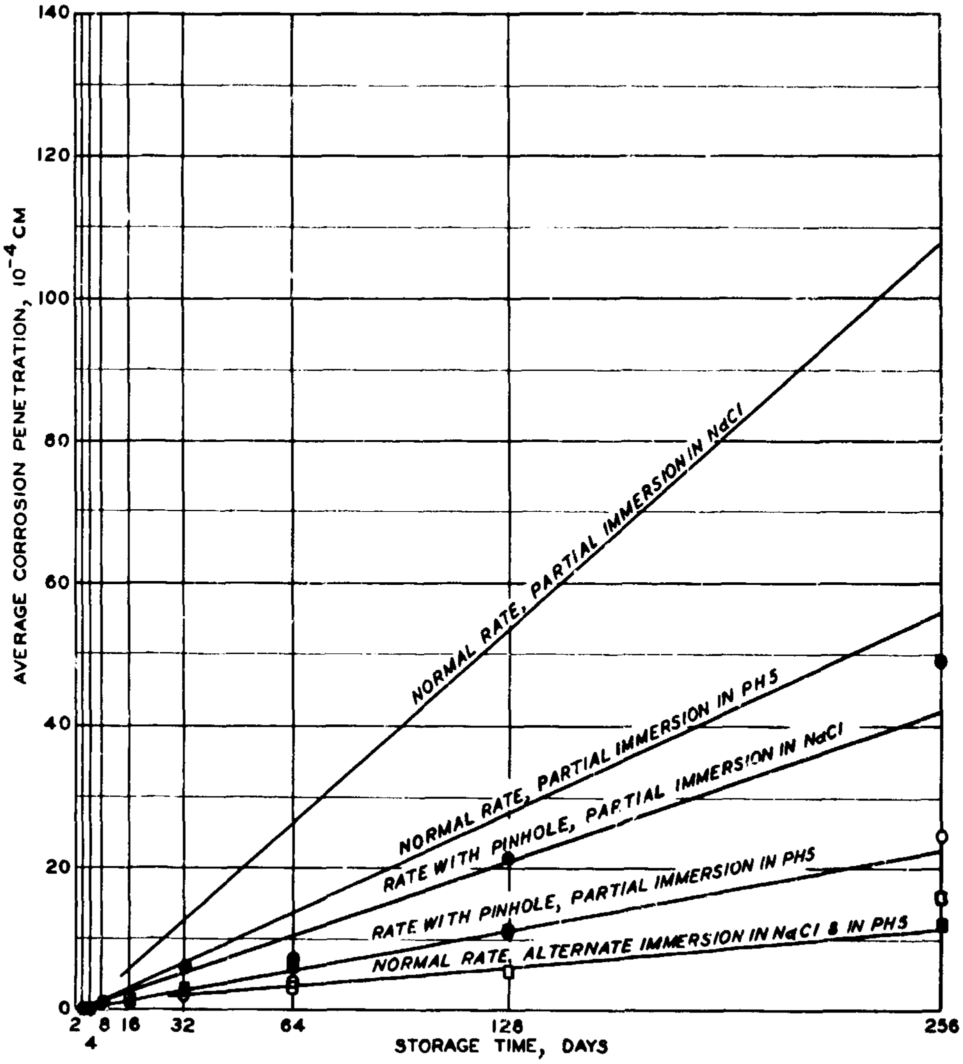
PLATE II



EFFECT OF 0.021-INCH PINHOLE ON CORROSION RATE

COPPERPLY

PLATE 12



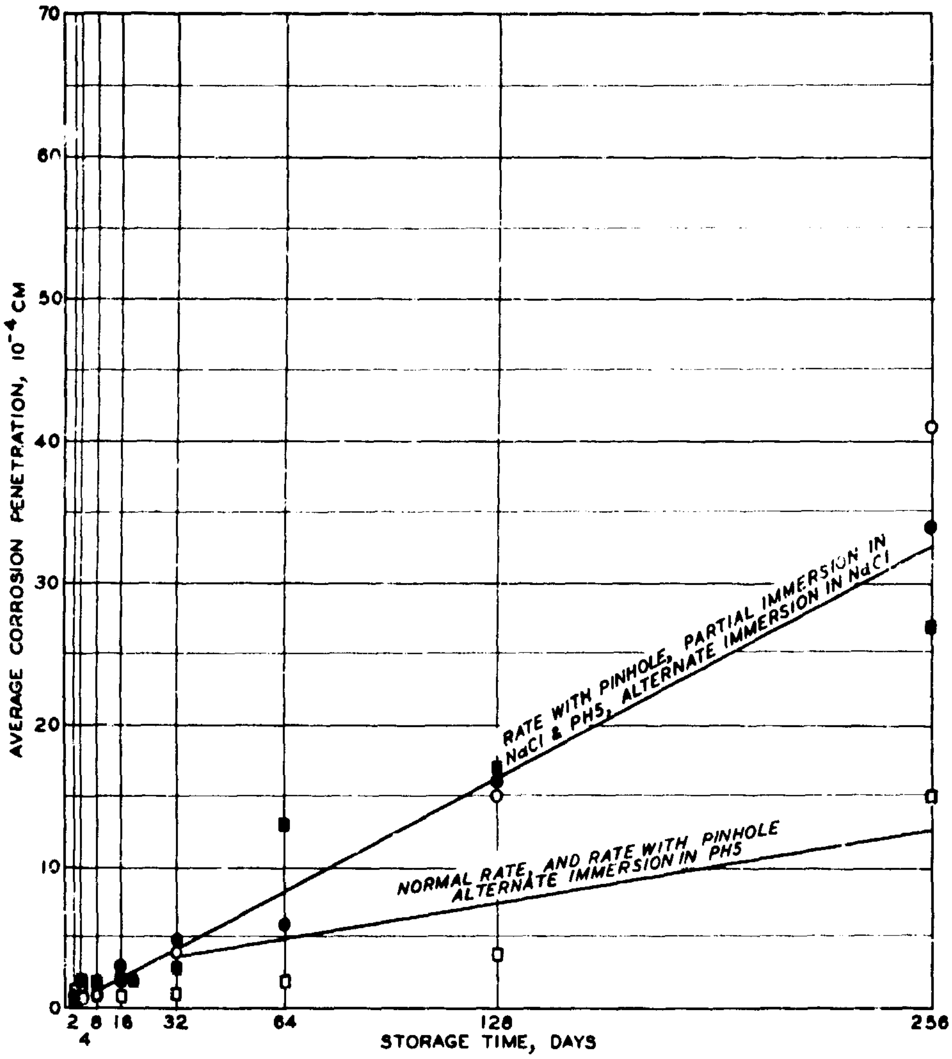
LEGEND

- ● PARTIAL IMMERSION IN NaCl
- O PARTIAL IMMERSION IN PH5
- ■ ALTERNATE IMMERSION IN NaCl
- □ ALTERNATE IMMERSION IN PH5

EFFECT OF 0.021-INCH PINHOLE ON CORROSION RATE

COPPERWELD

PLATE 13

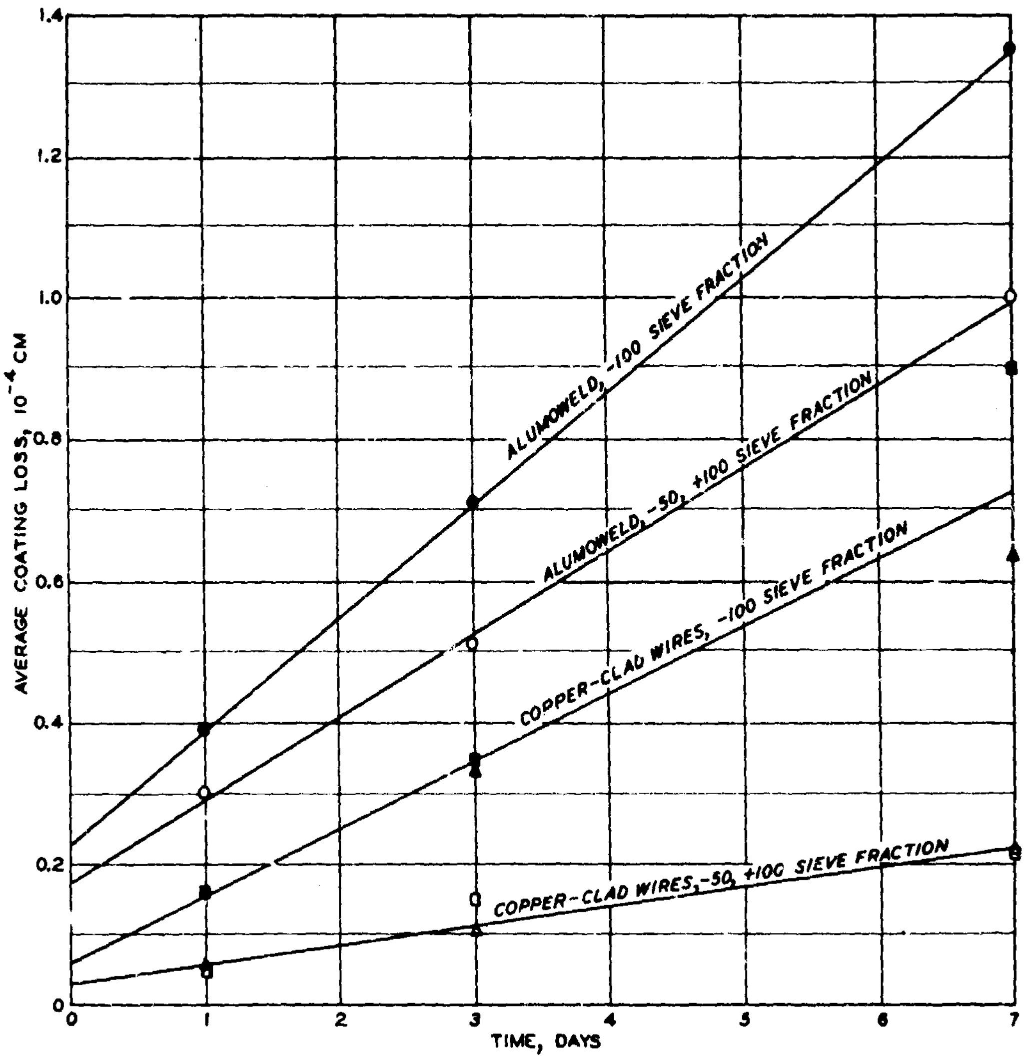


LEGEND

- ● PARTIAL IMMERSION IN NaCl
- ○ PARTIAL IMMERSION IN PH5
- ■ ALTERNATE IMMERSION IN NaCl
- □ ALTERNATE IMMERSION IN PH5

EFFECT OF
0.021-INCH PINHOLE
ON CORROSION RATE
ALUMOWELD

PLATE 14



LEGEND

	WIRE	SIEVE FRACTION OF SAND
●	ALUMOWELD	-100
○	ALUMOWELD	-50, +100
■	COPPERWELD	-100
□	COPPERWELD	-50, +100
▲	COPPERPLY	-100
△	COPPERPLY	-50, +100

RATE OF COATING LOSS DUE TO ABRASION BY A SLURRY OF NATURAL SILICEOUS SAND

APPENDIX A: METHODS OF TEST AND TEST REQUIREMENTS

TP 2-01. Physical Requirements. The fabric shall meet the following requirements:

a. Size of Wires. Wire used in manufacturing the fabric shall have a nominal diameter of not less than 0.182 inch nor more than 0.225 inch. Prior to beginning of manufacture, the Contractor shall advise the Contracting Officer of the diameter of the wire he proposes to use. A variation of 2 percent plus or minus from the approved nominal diameter will be permissible....

c. Tensile Strength. (1) Wire used in manufacturing the fabric shall have a breaking strength of not less than 4000 pounds in at least 75 percent and not less than 3600 pounds in the remaining 25 percent of the specimens tested.

(2) Fabrication Joints. Any joint or splice in a longitudinal wire shall have a tensile strength at least equal to that specified for the wire. At least 75 percent of the joints or splices in wires used as bracket wires in the fabric shall have a breaking strength of not less than 3,200 pounds, and the remaining 25 percent of the joints or splices in the bracket wires shall have a breaking strength of not less than 2,900 pounds. The end loops in the longitudinal wires of the fabric shall develop the same breaking strength specified for the wire. Joints fastening the bracket wires to the longitudinal wires in the fabric shall not reduce the specified breaking strength of the wires to less than 3,600 pounds and shall have a shearing resistance of not less than 100 pounds.

d. Bending. The wire from which the fabric is manufactured shall withstand a minimum of seven 90 degree bends without breaking and shall be capable of being wrapped around its own diameter 8 consecutive turns with a pitch substantially equal to the diameter of the wire without signs of imperfections....

TP 2-02. Tests for Materials. The Contractor shall furnish a certified chemical analysis of each heat of the metal, (core metal only for bimetallic wire,) from which wire for use in fabricating the fabric is drawn. In addition, the finished wire shall be subjected to the following tests to determine that it meets the requirements of these specifications:

a. Tensile Strength. Tensile tests to determine the breaking strength of the fabric wire and various portions of the fabric shall be made as follows:

(1) Straight unjointed pieces of the wire,

(2) End loops in each end of the longitudinal wire in the fabric,

(3) Joints or splices in the bracket and longitudinal wire,

(4) Pieces of wire on which joints fastening bracket wires to longitudinal wires have been made.

(5) Shear tests to determine the strength of joints fastening bracket wires to longitudinal wires.

At least one tensile strength test of the wire shall be made of each 5 coils of wire of approximately 200 pounds. One square from each 1,000 squares of fabric manufactured shall be selected and a tensile strength test made of at least two end loops in the end of the longitudinal wires; four joints in bracket wires; one joint or splice in the longitudinal wires; and three pieces of longitudinal wires and three pieces of bracket wires on which joints fastening bracket wires to longitudinal wires have been made. From this same square of fabric, three shearing strength tests of the joints fastening bracket wires to longitudinal wires shall be made. Should any specimen fail to meet the required tests, such additional tests as necessary to detect any other unsatisfactory wire or fabric shall be made, and all wire or fabric failing to meet the requirements set forth in paragraph TP 2-01c shall be rejected.

b. Bending. The following tests shall be made from each five coils of approximately 200 pounds of the wire from which the fabric is to be manufactured:

(1) A length of wire shall be held between jaws having edges rounded on a 3/8" radius. The free end of the wire shall be bent over the rounded edges back and forth through an angle of 180° between limiting positions on opposite sides of, and at right angles to, the original straight wire. Specimens shall be straight and shall extend approximately 10 inches from the support. Bends shall be made at as nearly a uniform speed as possible, not exceeding 50 bends per minute and in no case shall the speed be so great as to cause undue heating of the wire. Each 90° movement in either direction shall be counted as one bend. The number

of bends shall be counted until the specimen is severed. When failure occurs, 90 percent of the specimens shall have withstood at least 7 bends. Bi-metallic wire, when broken by repeated bending, shall show no separation of the covering from the core metal.

(2) A length of wire shall be wrapped around its own diameter 8 consecutive turns with a pitch substantially equal to the diameter of the wire without signs of imperfections.

Failure of these tests will result in rejection of the wire represented by the sample.

c. Quality of Coating of Bi-Metallic Wire. The following test of the quality of coating of bi-metallic wire shall be made on one specimen from each coil of approximately 200 pounds of wire:

Lengths of wire after having been wrapped as prescribed in paragraph TP 2-02b(2) shall be subjected to a ferroxyl test to be made as follows:

First: Samples shall be immersed in a 15% solution by weight of hydrochloric acid for approximately one hour or in a 50% solution of hydrochloric acid for approximately 3 minutes to remove ferrous contamination of the surface. If surface contamination is still present, the wire may be immersed for 10 seconds in a 50% solution of nitric acid.

Second: Sample shall then be immersed for one minute in a solution of:

10 grams of Potassium Ferricyanide
1000 cc Distilled Water
20 grams of Concentrated Sulphuric Acid

The appearance of blue spots or lines on the samples indicates porosity, flaking, cracks, or interstices showing the solution is in contact with the steel core. If this occurs, four additional specimens shall be prepared and subjected to the ferroxyl test. Failure of any of these retest specimens will result in rejection of material covered by the tests

d. Thickness of Coating. Thickness of coating of bi-metallic wire shall be determined by one of the following methods on each coil of approximately 200 pounds of wire from which fabric is to be manufactured:

(1) After thoroughly cleaning the test specimens with carbon tetrachloride, or other grease remover, they shall be immersed in nitric acid for approximately 30 seconds or longer, and then removed and quickly immersed in water to stop the action of the acid. This cycle shall be repeated until the diameter of the wire shall have been reduced at least 2 times the guaranteed minimum thickness of the metallic covering for a length of not less than 1/2 inch. If pitting should occur during this treatment, the specimen shall be burnished with steel wool. At that part of the wire which shows a reduction in diameter of 2 times the guaranteed minimum thickness of the copper covering when measured with a micrometer, the wire shall remain covered with the coating. If any core metal should be visible at any point where the specimen measures two times the guaranteed minimum thickness of the covering less than the original diameter, a microscopic measurement of a duplicate specimen shall be made. Should the microscopic measurement show the covering to be less than the guaranteed minimum thickness of the covering, the coil of wire which the specimen represents shall be rejected.

(2) Removing sufficient coating and accurately gaging with suitably accurate apparatus.

(3) Cutting off the wire, grinding smooth, and etching its exposed cross section, and gaging by suitably accurate apparatus.

(4) Using electrical indicating instruments of suitable accuracy.